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Development of an Updated Hydrogeologic Conceptual Model and a Numerical Groundwater Flow Model at RMC-Troutdale

TECHNICAL MEMORANDUM NO. GW-20

Volume 1: Text, Tables, and Appendixes

Reynolds Metals Company
TROUTDALE FACILITY

CH2MHILL

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Abbreviations and Acronyms

bgs	below the ground surface
BLA	Blue Lake Aquifer
BPA	Bonneville Power Administration
cfs	cubic feet per second
cm/sec	centimeters per second
COE	U.S. Army Corps of Engineers
COP	City of Portland
CU1	Confining Unit 1
CU2	Confining Unit 2
DEQ	Oregon Department of Environmental Quality
EPA	U.S. Environmental Protection Agency
FEMA	Federal Emergency Management Agency
gpd	gallons per day
gpm	gallons per minute
gpm/ft	gallons per minute per foot
GS&G	Gresham Sand and Gravel
mgd	million gallons per day
mg/L	milligram(s) per liter
MSL	mean sea level
NGVD	National Geodetic Vertical Datum
PWB	Portland Water Bureau
RMC	Reynolds Metals Company
SGA	Sand and Gravel Aquifer
TGA	Troutdale Gravel Aquifer
TSA	Troutdale Sandstone Aquifer
UGS	upper gray sand
USA	Unconsolidated Sedimentary Aquifer

Development of an Updated Hydrogeologic Conceptual Model and a Numerical Groundwater Flow Model at RMC-Troutdale

PREPARED FOR:	Steve Shaw/RMC
PREPARED BY:	John Porcello/CH2M HILL-PDX
COPIES:	Mike Leach/RMC Doug Macauley/RMC Ken Trotman/CH2M HILL-SEA
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Introduction

This technical memorandum describes the development of an updated hydrogeologic conceptual model and a site-scale numerical groundwater flow model at the Reynolds Metals Company (RMC) aluminum reduction facility in Troutdale, Oregon. The site-scale numerical flow model was constructed as a tool to evaluate the effectiveness of various groundwater remedial alternatives for the multi-layer aquifer underlying the facility. The model was also constructed to support the groundwater baseline risk assessment and subsequent analyses of the degree of risk reduction that would occur under various groundwater remedial alternatives.

The term "site-scale" pertains to the model's ability to simulate the groundwater flow system at and near the facility, including aspects of surface water-groundwater interactions and RMC production well pumping. Groundwater flow directions and velocities at the site are influenced by precipitation recharge, shallow surface drainages (South Ditch, Salmon Creek), the shallow dewatering system at the bakehouse, Company Lake, production well pumping, and the Columbia and Sandy Rivers (which fluctuate in response to tides, precipitation, and dam releases). Because of the number and complexity of influences on the groundwater system, RMC concluded that a numerical model would be useful for evaluating the effectiveness of proposed groundwater remedial alternatives.

The site-scale numerical flow model was constructed using information presented in the *Preliminary Conceptual Hydrogeologic Model* (CH2M HILL, March 21, 1996) and recent data collected at the facility. The primary source of additional data was the Fairview Farms aquifer test, a 26-day test conducted in September 1997 (CH2M HILL, July 23, 1998). The purpose of the aquifer test was to provide water level data on and around the RMC facility under pumping conditions that would facilitate model calibration. The test was specifically designed to stress the aquifer to a sufficient degree that the model calibration effort would be able to evaluate the sitewide effects of pumping onsite and from the Fairview Farms property. The understanding of the site hydrogeology was greatly refined during the course of the model construction and calibration effort, based on the simulation of the Fairview Farms aquifer test. Consequently, this technical memorandum documents not only the numerical modeling work, but also the revisions to the conceptual model that pertain to the construction, calibration, and predictive use of the numerical model.

Organization

This technical memorandum is organized in two main sections, as described below.

Section 1: Updated Conceptual Hydrogeologic Model

- **Section 1.1: Recent Data Collection Activities.** This section describes the primary data collection activities that have been performed at the facility since the publication of the *Preliminary Conceptual Hydrogeologic Model* (CH2M HILL, March 21, 1996).
- **Section 1.2: Regional Geologic Framework.** This section presents updated interpretations of the regional geology, including the regional hydrogeologic structure and regional stratigraphy.
- **Section 1.3: Site Geologic Framework.** This section discusses the site stratigraphy and the elevation of the base of the unconsolidated water-bearing deposits underlying the site.
- **Section 1.4: Site Hydrogeology.** This section discusses the hydraulic properties of the aquifer and the influence of river stages and wellfield pumping on groundwater flow in each water-bearing zone. This section includes discussions of groundwater response data for the 26-day Fairview Farms aquifer test, including groundwater elevation contour maps and hydrographs of groundwater elevations and vertical gradients at observation well clusters.
- **Section 1.5: Onsite Surface Water Features and their Interaction with Groundwater.** This section describes the interactions between groundwater and surface water features both onsite and north of the flood control dike.

Section 2: Numerical Model Development

- **Section 2.1: Model Objectives and Model Selection.** This brief section describes the modeling objectives and the software that was used.
- **Section 2.2: Model Construction.** This section includes discussions of the model layering, boundary locations, boundary conditions, and design of the model mesh.
- **Section 2.3: Model Calibration.** This section presents a discussion of the model calibration effort, including the establishment of calibration criteria, the comparison of simulated and observed water level responses to the Fairview Farms aquifer test.
- **Section 2.4: Calibration Check.** This section describes particle-tracking analyses that were conducted to evaluate the model's ability to simulate the groundwater flow patterns that have governed the distribution of fluoride in groundwater. The particle-tracking analyses evaluated long-term historical pumping patterns, as well as a hypothetical no-pumping scenario.

This technical memorandum contains the following appendixes:

- Appendix A: Fairview Farms Aquifer Test
- Appendix B: Description of Micro-Fem® Groundwater Flow Model
- Appendix C: Well Locations with Fixed Nodes in the Finite-Element Mesh
- Appendix D: Construction Summary of Groundwater Monitoring Wells, Production Wells, and Other Wells
- Appendix E: Elevation Data for the Base of the Silt Unit and the Top of the Older Rocks Unit

Volume 1 of this technical memorandum contains the text, tables, and appendixes. Volume 2 contains the figures that are referenced in Volume 1.

Nomenclature for Water-Bearing Zones

The unconsolidated sediments within the uppermost regional groundwater system beneath the RMC facility have been subdivided into four water-bearing zones during the course of the investigations conducted since 1994. The four zones are defined by the site stratigraphy and the depths at which monitoring wells have been constructed. These four zones and their nomenclature are:

- **Silt Unit.** Where present, the silt unit extends from ground surface to approximately 30 feet below the ground surface (bgs). The silt unit is also referred to in this report as the "silt."
- **Upper Gray Sand (UGS).** The UGS extends to a depth of approximately 50 feet bgs. It is present at ground surface north of the flood control dike and lies beneath the silt unit south of the dike.
- **Intermediate Sand.** The intermediate sand extends from the base of the UGS to a depth of 100 feet bgs and is also referred to in this report as the "Intermediate Zone."
- **Deep Sand/Gravel.** The deep sand/gravel extends from the base of the intermediate sand to a depth of 200 feet bgs and is also referred to in this report as the "Deep Zone" or "Deep Sand."

SECTION 1

Updated Conceptual Hydrogeologic Model

SECTION 1

Updated Conceptual Hydrogeologic Model

The current conceptual model of the hydrogeology at RMC-Troutdale is based on a preliminary conceptual model and on subsequent data collection activities. The *Preliminary Conceptual Hydrogeologic Model* (CH2M HILL, March 21, 1996) presented detailed discussions of the regional and site geology, groundwater and surface water hydrology, and groundwater and surface water quality. The report also presented a local groundwater use survey, geologic logs for monitoring wells and production wells (onsite and offsite), and results of short-term aquifer tests and slug tests conducted during 1995. This information and subsequent data collection activities are pertinent to model construction and calibration. This section of the technical memorandum discusses the scopes and objectives of the additional data collection activities and presents the aspects of the updated conceptual hydrogeologic model that pertain to the modeling work.

1.1 Recent Data Collection Activities

Numerous data have been collected at the facility since the publication of the *Preliminary Conceptual Hydrogeologic Model* (CH2M HILL, March 21, 1996). The following data collection activities were of significance to the modeling effort. (See Figure 1-1[1] for the locations of key site features, including RMC's active production wells and existing groundwater monitoring wells.)

1.1.1 Sitewide Aquifer Testing Program

This program is described in *Technical Memorandum No. GW-16: Aquifer Test Results, RMC-Troutdale* (CH2M HILL, July 23, 1998). The objective of this program was to collect data that could be used to calibrate the site-scale numerical flow model and that would improve and update the conceptual hydrogeologic model. The specific tests conducted were:

- The Fairview Farms aquifer test, which was a 26-day aquifer test conducted during September 1997 that involved pumping two deep RMC production wells (PW03 and PW07) and a deep well in Fairview Farms (FF04). The test is described in Appendix A.
- Slug tests at 35 monitoring wells completed in the upper gray sand (UGS) and the intermediate and deep sand zones. Slug testing of wells contained in the silt unit was described in the *Preliminary Conceptual Hydrogeologic Model* (CH2M HILL, March 21, 1996).
- Short-term aquifer testing of 12 monitoring wells completed in the UGS. The wells were pumped at constant rates for periods of 5 to 8 hours using a Grundfos® centrifugal pump.

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[1] All figures are bound separately in Volume 2. All tables appear after the text of this technical memorandum.

1.1.2 Installation of Additional Monitoring Wells

Sixty-three new monitoring wells and 22 shallow piezometers were installed during 1996 and 1997. The geologic data and water quality data collected from these locations improved the understanding of the site hydrogeology and the nature and extent of fluoride in groundwater.

1.1.3 Geoprobe® Installation

Forty-eight temporary Geoprobes were installed throughout the RMC property during August 1997 to improve the understanding of the nature and extent of fluoride in groundwater. This work is described in *Technical Memorandum No. GW-12: August 1997 Quarterly Groundwater Monitoring Results* (CH2M HILL, December 18, 1997). During the model calibration process, concentration contour maps constructed from these data (and from monitoring well data) were compared with particle-tracking results from the model to assess the quality of the model calibration.

1.1.4 Groundwater Level Monitoring

Monthly rounds of sitewide water level measurements were conducted from 1996 through 1997. Quarterly rounds were conducted during 1998. These data, which have been reported in monitoring reports throughout this period, show the effects of increased pumping from the RMC production wells during these years. This information has improved the understanding of the effects of pumping on vertical gradients beneath the RMC property. In addition, continuous water level data were collected in the Sandy and Columbia Rivers and in adjacent monitoring wells over a 1-month period following completion of the Fairview Farms aquifer test. This monitoring was performed to improve the understanding of groundwater/surface water interactions and is described in the *Draft Surface Water and Sediment Areas Addendum to the RI/FS Work Plan* (CH2M HILL, April 3, 1998). In addition to the data collection for the aquifer test and the analysis of groundwater/surface water interactions, continuous water level monitoring was performed at various monitoring wells from 1995 through 1997.

1.1.5 Soil and Debris Area Field Investigation Programs

Investigations were conducted during 1997 and the summer of 1998 on the nature and extent of fluoride in debris and underlying soils (the silt unit and the UGS). The 1997 investigations are described in *Technical Memorandum DS No. 16: Data Summary for the Soil and Debris Areas Addendum to the RI/FS Work Plan* (CH2M HILL, December 15, 1997). The 1998 investigations are described in Appendix B of the *Draft Groundwater Remedial Investigation Report* (CH2M HILL, in progress).

1.1.6 Data Collection at Company Lake and South Ditch

Physical data and fluoride concentration data collected at these two locations are documented in several technical memorandums:

- *Technical Memorandum DS No. 15: Company Lake Supplemental Data Summary* (CH2M HILL, March 26, 1997)

- *Technical Memorandum DS No. 17: Data Summary for the Wastewater Discharge Areas Addendum to the RI/FS Work Plan, Part 1* (CH2M HILL, December 12, 1997)
- *Technical Memorandum DS No. 18: Data Summary for the Wastewater Discharge Areas Addendum to the RI/FS Work Plan, Part 2* (CH2M HILL, June 17, 1998)

These documents include topographic data for the bed of the ditch, bathymetric data for the lake, permeability data for the process residue and underlying sediments, and a water balance for the lake that estimated the leakage rates to groundwater during the Fairview Farms aquifer test.

1.1.7 Additional Data

In addition to the data collection activities at the site, additional hydrogeologic data in the surrounding area became available. Most significant to the model calibration effort was a report prepared for the Portland Water Bureau (PWB) that presented geologic logs and interpretations from monitoring well construction activities conducted at the Blue Lake Aquifer (BLA), which extends west from the western boundary of Fairview Farms. This report (Roger N. Smith Associates, Inc., 1997) provided information that refined the understanding of the location of the eastern extent of the BLA.

1.1.8 Elements of the Conceptual Hydrogeologic Model

The rest of Section 1 presents the following information pertaining to the refined hydrogeologic conceptual model:

- A refined understanding of the geologic framework, which includes:
  - Refinements to the regional and site-scale geologic cross sections and construction of two new site-scale sections
  - A contour map of the elevation of the base of the regional unconsolidated aquifer system [which consists of the Unconsolidated Sedimentary Aquifer (USA) and the underlying Sand and Gravel Aquifer (SGA)]
- A refined understanding of the groundwater system beneath the site, including:
  - Hydraulic properties of each unit (including horizontal and vertical hydraulic conductivities)
  - The effects of production well pumping and river stage fluctuations on horizontal and vertical groundwater flow patterns
- Onsite surface water features and their interactions with groundwater

1.2 Regional Geologic Framework

As discussed in the *Preliminary Conceptual Hydrogeologic Model* (CH2M HILL, March 21, 1996), the primary hydrogeologic units beneath the RMC site are the USA and the SGA. In areas south and west of the site, these two units are present along with the Troutdale Sandstone Aquifer (TSA) and two low-permeability units that are called Confining Units 1 and 2 (CU1 and CU2). A productive unconsolidated unit, the BLA, also lies west of the RMC facility. The following subsection discusses the regional hydrogeologic structure and stratigraphy.

1.2.1 Regional Hydrogeologic Structure

Figure 1-2 shows a surface map of the hydrogeologic units present near the RMC facility. This figure also shows the locations of subsurface geologic cross sections A-A′ and B-B′, which are presented in Figures 1-3 and 1-4, respectively. The map and sections have been prepared from reviews of geologic logs for production wells and monitoring wells completed in the area. In addition, the preparation of these sections has incorporated interpretations contained in reports by Swanson et al. (1993), Bet and Rosner (1993), and Roger N. Smith Associates, Inc. (1997).[2]

The surface geologic map shows the following structural features:

- The RMC facility is situated on top of the USA. In areas west and southwest of the site, the Troutdale Formation [consisting of the TSA and the Troutdale Gravel Aquifer (TGA)] is exposed at the ground surface in many locations. These exposures compose a dome that is the structural high point of a large regional fold. Information from borehole geophysical logs and other well logs indicates that the northeast portion of the structural dome was cut by the east-west trending fault shown in Figure 1-2 (Bet and Rosner, 1993).
- Along the northeast flank of this structural dome, the Troutdale Formation is absent. This is likely the result of erosion that occurred during large-scale flooding events associated with outbursts from Pleistocene-age glacial Lake Missoula. The flooding removed the Troutdale Formation after it was uplifted, creating a trough along the fault plane that was subsequently filled with the coarse paleo-channel sediments that constitute the BLA (Bet and Rosner, 1993).

1.2.2 Regional Stratigraphy

The stratigraphy in the vicinity of the RMC facility is shown in the two regional cross sections (Figures 1-3 and 1-4).

1.2.2.1 West-East Regional Cross Section

Figure 1-3 is a west-east trending cross section (A-A′) that shows the following:

- The unconsolidated materials that form the USA beneath the RMC facility were deposited into a deep trough by the Columbia and Sandy Rivers. This is indicated by the following observations:
  - Confining Units CU1 and CU2, and the regional water-bearing units (including the TGA and TSA), are not present beneath the USA in the RMC site vicinity. Their absence is thought to be the result of erosion by the ancestral Columbia River.

[2] Large-scale regional cross sections of the Portland Basin are not presented in this report because several of the aquifer units within the basin are not present in the vicinity of the RMC site. Refer to Plates 1 and 2 in Swanson et al. (1993) for regional cross sections of the Portland Basin.

- The well logs for the deepest RMC production wells (PW10 and PW14) indicate the presence of relatively uniform sands within the USA, with the upper portion of the underlying SGA consisting of a mixture of sands with occasional silt and gravel layers having variable colors and degrees of lithification. Deeper portions of the SGA contain mixtures of sand, gravel, and cemented gravel. The heterogeneity and depth of the deep SGA materials suggests that they are deposits from both the Columbia and Sandy River systems that were dropped into a deep trough. The upper SGA, which has a greater percentage of sand than the lower SGA, may also consist of bed-load deposits from both river systems. In contrast, the USA deposits are delta deposits associated with the Sandy River bed load, which consists of gray sands.

- The well log from the deepest RMC production well (PW10) indicates a hard shale zone at about 550 feet below the ground surface (bgs). It is probable that the shale referenced on the driller's log is a thin, platy basalt sequence rather than an actual shale unit, and it therefore likely represents the top of the Older Rocks sequence defined by Swanson et al. (1993).

- Between the BLA and the RMC facility, the geologic contact between the SGA and the overlying USA is based on the geologic logs for PWB monitoring wells BLA-3 and PWB-5 (Roger N. Smith Associates, Inc., 1997) and RMC production wells PW10 and PW17. The top of the SGA is defined at wells PW10 and PW17 by a contact between sands and underlying fine-grained materials (defined in the drillers' logs as silt, sandy silt, clay, and hard-packed sand). At monitoring well PWB-5, the top of the SGA is defined by the contact between relatively unconsolidated sands and silts and underlying semiconsolidated deposits of gravel and sandstone.

- The BLA's eastern edge lies approximately 1 ¼ miles west of Sundial Road, which forms the western property boundary of the RMC facility. The eastern extent of the BLA is defined by the recent installation of PWB monitoring wells BLA-3 and PWB-5 (Roger N. Smith Associates, Inc., 1997) and from inspection of geologic logs for City of Portland (COP) well Nos. 13, 17, and 18. These data indicate that the upper portion of the BLA is bounded to the east by CU2.

- The upper USA water-bearing zone overlies the BLA and is likely in hydraulic communication with it. On the basis of drillers' logs for COP production wells and monitoring wells, the BLA and SGA are thought to be separated by CU2. The material beneath the BLA at COP well No. 13 is interpreted to be CU2, rather than the SGA, based on the geologic log's description of blue clay directly beneath the BLA at a depth of 173 feet bgs. In addition, the remaining drilled depth encountered blue clay and other materials as described in the geologic log. However, the CU2 may be absent beneath a limited portion of the BLA according to other published geologic cross sections (Roger N. Smith Associates, Inc., 1997), leaving portions of the BLA in possible hydraulic connection with the SGA.

Compared with the cross section (Figure 3-4) contained in the *Preliminary Conceptual Hydrogeologic Model* (CH2M HILL, March 21, 1996), the west-east regional cross section (A-A′) was revised as follows:

- The eastern extent of the BLA was refined using recent geologic data. The revision was based on the geologic log for PWB monitoring well BLA-3 (Roger N. Smith Associates, Inc., 1997) and geologic logs for COP well Nos. 13, 17, and 18. These data indicate that the upper portion of the BLA is bounded to the east by CU2.
- The material beneath the BLA at COP well No. 13 was reinterpreted to be CU2, rather than the SGA. This is based on the geologic log's description of blue clay directly beneath the BLA at a depth of 173 feet bgs. In addition, the remaining drilled depth encountered blue clay and other materials as described in the geologic log.
- Between the BLA and the RMC facility, the geologic contact between the SGA and the overlying USA was refined based on the geologic logs for PWB monitoring wells BLA-3 and PWB-5 (Roger N. Smith Associates, Inc., 1997).

1.2.2.2 Northwest-Southeast Regional Cross Section

The northwest-southeast trending cross section (B-B′ in Figure 1-4) depicts the following:

- The USA is present as a 200-foot-deep sedimentary channel beneath the RMC facility. It thins dramatically beginning approximately one-half mile southeast of the site. In this area, the USA is underlain by the TSA and CU2, which both lie above the SGA. Farther south, near the City of Troutdale, the geologic log for COP well No. 4 shows the thicker sequences of both the TSA and CU2. COP well No. 4 taps groundwater from the SGA at depths between 493 and 563 feet bgs.
- The deepest materials encountered under the site are the basalt flows and consolidated volcanic rock debris associated with the Older Rocks unit. The unit crops out in the Columbia River to the north-northwest of the site. Exposures are observed at Ione Reef (about river mile 120) and at the eastern border of Lady Island.
- The top of the Older Rocks unit dips sharply to the south and, south of the site, is present at a depth exceeding 750 feet, based on the geologic log for the Troutdale Airport well. The log for this well, which was drilled using air rotary methods, indicates that the materials consist of interbedded layers of blue sands, blue clay, and "broken rock" from a depth of about 261 feet to the well's total depth (750 feet). This description makes it difficult to interpret whether these materials are associated with the SGA or with the Older Rocks. However, the log does indicate that the static water level in the well (which is screened over a depth interval of 435 to 750 feet) was recorded as 20 feet bgs after completion of the well. This depth is equivalent to an elevation of about 10 feet, which is similar to the average stage in the Columbia River. In addition, the specific capacity of the well was recorded as 14 gallons per minute per foot (gpm/ft), which is similar to the specific capacities indicated on the drillers' logs for the two deepest RMC production wells (PW10 and PW14, which have specific capacities of 23 and 10 gpm/ft, respectively).[3] In addition, the Troutdale Airport well is screened at a depth interval

[3] The original design and construction of a well, along with its maintenance, can affect the specific capacity of a well. These factors can have as significant an influence on the specific capacity of a well as the hydraulic conductivity of the aquifer formation. In this case, the drillers' logs for wells PW10 and PW14 show specific capacities that are lower than the specific capacities indicated on drillers' logs for shallower RMC production wells (which range from 21 gpm/ft at PW07 to 95 gpm/ft at PW05).

similar to PW10 and PW14, which have screened intervals of 440-558 and 608-637 feet bgs, respectively. Consequently, these data suggest that the Troutdale Airport well is completed in the SGA and does not extend into the Older Rocks. This interpretation is also consistent with regional interpretations that indicate that the Older Rocks lie at an elevation of about 800 feet below mean sea level. (See Plate 3 in Swanson et. al, 1993.)

Compared with the cross section (Figure 3-5) contained in the *Preliminary Conceptual Hydrogeologic Model* (CH2M HILL, March 21, 1996), the north-south regional section (B-B′) was revised based on the addition of well PW10 to the section (at the intersection with regional section A-A′) and reexamination of the geologic logs at nearby wells PW16 and PW17. Specific changes were:

- The contact between the USA and the SGA was raised directly beneath the RMC facility. This contact, which was originally set at a depth of approximately 250 to 270 feet, is shown in Figure 1-4 at a depth of about 190 to 200 feet. This revision was based on a color change described in the geologic logs from gray to blue materials. Specifically, the origin of the blue materials is interpreted to be from deposition and reworking of sediments from both the Columbia and Sandy Rivers. In contrast, the gray materials are interpreted to be Sandy River delta deposits. The contact between the USA and SGA was also revised based on the placement of the uppermost well screens at and above this interval in wells PW10 and PW16. Specifically, the uppermost screens were probably not extended deeper because of reduced yields. Consequently, the revised USA/SGA contact is likely a hydraulic contact, as well as a geologic contact.
- A contact between the USA and the SGA is shown in Figure 1-4 north of the dike. This contact is drawn based on the revised elevation for the contact south of the dike, as well as the description of interbedded sand and gravel sequences in monitoring wells constructed north of the dike (particularly MW08 and MW27).
- The contact between the SGA and the underlying Older Rocks south of the RMC facility was redefined based on the log for the Troutdale Airport well. As discussed previously, the Troutdale Airport well is completed in the SGA and does not extend into the Older Rocks.

1.3 Site Geologic Framework

This section discusses site stratigraphy (using seven site-scale geologic cross sections) and the elevation of the contact between the SGA and the underlying Older Rocks unit.

1.3.1 Site Stratigraphy

Figure 1-5 shows the locations of seven geologic cross sections that were constructed at a site scale. Figures 1-6 through 1-12 present the seven cross sections (C-C′ through J-J′). These cross sections update those contained in the *Preliminary Hydrogeologic Conceptual Model* (CH2M HILL, March 21, 1996), based on the groundwater monitoring well construction and other data obtained since that time.

Table 1-1 summarizes the objectives of each cross section and the rationale for each cross section's alignment. Key observations from the site-scale cross sections are as follows:

- A sequence of well-sorted sands approximately 400 feet thick is present from RMC production well PW18 south toward the Troutdale Airport well. (See Figure 1-6.) This thick sequence of sands is also present in the southwestern portion of the site and likely thins to the west because of a rise in the top of an underlying gravel sequence. (See Figure 1-12.) At the Troutdale Airport well, the well-sorted sand is absent below a depth of about 260 feet, where interbedded silty and gravelly clays are present.
- North of PW18, the thick sequence of well-sorted sand contains a distinct 20- to 60-foot-thick layer of silt and sandy silt that is present at a depth of approximately 175 feet bgs. (See Figure 1-6.) This sequence thins to the south, and in the western portion of the site it appears to dip from north to south. (See Figure 1-11.) Figures 1-6 and 1-11 show that RMC production wells PW10, PW14, PW16, and PW18 all were constructed with screened intervals immediately above this unit. Figure 1-8 also shows a similar placement of the screened interval at RMC production well PW05.
- Immediately north of the potlines, sands are present only to the top of the silt/sandy silt layer, which is underlain by gravel rather than sand. North of cross section E-E′, the silt/sandy silt layer is absent, and the sand unit and the gravel unit both thin to the north because of a sharp rise in elevation of the top of the Older Rocks unit. (See Figures 1-6 and 1-11.)
- The two cross sections immediately north of the potlines, Sections D-D′ and E-E′ (see Figures 1-7 and 1-8), show that the well-sorted sand sequence is underlain predominantly by gravels to the west. Some of these gravels are cemented, as indicated by the geologic log for MW29. Just east of MW29, the gravels are deeper, with a sequence of silt and interbedded sand separating the overlying clean sands and the underlying gravels. From PW08 to the east, the silt layer is absent and the 400-foot-thick sand sequence is present, including a 20- to 40-foot-thick cemented gravel layer at a depth of approximately 100 to 150 feet bgs. (See wells PW05, PW08, MW10, and MW33.) This thick sequence of sands and a single interbedded cemented gravel layer are also present north of the dike, as shown in Figures 1-9 and 1-10.
- The cross sections show the presence of a silt/sand layer lying above the UGS across the site. Recent drilling activities have resulted in subdivision of this layer (called the silt unit) into a surficial sand layer and an underlying silt layer (which are not shown because of the vertical scales of the cross sections). The surficial sand layer is typically less than 10 feet thick and is absent in places. It lies below the water table in some locations during the summer. Throughout most of the area south of the flood control dike, the silt layer is below the water table and has a typical thickness of 20 feet. North of the dike, the silt layer is much thinner and is not situated beneath the water table except during extremely wet seasons.

1.3.2 SGA Base Elevation

Figure 1-13 shows an elevation contour map of the top of the Older Rocks, which form the base of the SGA. The map shows that the Older Rocks rise from south to north and are present at ground surface along the northern shore of the Columbia River. A ridge is also present along this southward-dipping surface, extending from Ione Reef south beneath

Company Lake and the RMC potline buildings. The depth of the bedrock surface beneath the RMC facility is based on geologic logs from the RMC production wells. In areas surrounding the RMC facility, the depth contours are based on interpretations by Swanson et. al (1993).

1.4 Site Hydrogeology

The following topics regarding the site hydrogeology are discussed below:

- The hydraulic properties of the four primary water-bearing zones (the silt unit, the UGS, the intermediate zone, and the deep zone) (Section 1.4.1)
- The influences of river stages and onsite pumping on groundwater flow in the intermediate and deep zones (Section 1.4.2) and in shallower zones (Section 1.4.3)

1.4.1 Hydraulic Properties

The horizontal hydraulic conductivities of the silt unit, the UGS, and the intermediate and deep sand zones have been estimated using data collected from the January-September 1997 sitewide aquifer testing program (CH2M HILL, July 23, 1998). Tables 1-2, 1-3, 1-4, and 1-5 provide statistical summaries of measured hydraulic conductivity values for the silt unit, the UGS, the intermediate zone, and the deep zone, respectively. On the basis of the tabulated results, typical values of the horizontal hydraulic conductivity are estimated to be:

- Silt unit: 1 to 2 ft/day
- UGS: 35 ft/day along and north of the flood control dike, 2 ft/day on the plant site
- Intermediate sand: 100 to 120 ft/day according to short-term testing data, but 150 to 160 ft/day according to slug test data
- Deep sand: Variable according to location and type of test performed. Excluding the short-term test data, which produce unreasonably low values, the distribution of horizontal hydraulic conductivities is as follows:
  - Eastern portion of the site: 100 to 120 ft/day
  - Site interior: 130 to 175 ft/day
  - Fairview Farms and western portion of the site: 75 ft/day according to slug test data, 150 ft/day according to the Fairview Farms aquifer test data

These values were estimated by fitting water level data collected during each test to the analytical equations listed in the tables. The hydraulic conductivity estimates contained in the tables were used during model calibration primarily as initial estimates of aquifer properties. They were adjusted throughout calibration based on simulations of the water level data collected during the 26-day Fairview Farms aquifer test.

The vertical hydraulic conductivity of the silt unit was measured during the 1998 field investigation in four soil samples collected from the three soil and debris areas (scrap yard, east potliner, and south landfill) located in the South Plant area. Table 1-6 summarizes the vertical hydraulic conductivity data, as well as other physical parameters that were measured in these samples. For the silt unit, the vertical permeability ranged from between 0.0003 and 0.0006 ft/day [approximately 10^{-7} centimeters per second (cm/sec)] beneath south landfill and east potliner and 0.006 ft/day (approximately 2×10^{-6} cm/sec) beneath the scrap yard. On the basis of these results and the horizontal hydraulic conductivity values for the silt unit (1 to 2 ft/day), the ratio of horizontal to vertical hydraulic conductivity (the Kh:Kv ratio) is estimated to be between 100:1 and 1,000:1 for the lowest permeability soils and about 100:1 for the somewhat more permeable silts situated beneath the scrap yard.

Vertical hydraulic conductivities were not directly measured in the underlying sand units. The upper gray sand unit contains variable amounts of fine-grained materials and likely has a Kh:Kv ratio of 100:1 or less. Because the intermediate and deep sand units generally contain very low amounts of fine-grained materials, the Kh:Kv ratio is likely substantially less than 100:1.

1.4.2 Influences of River Stage and Wellfield Pumping on Groundwater Flow in the Intermediate and Deep Zones

Long-term monitoring of water levels and river stages at the RMC facility has shown that the stages of the Columbia and Sandy Rivers affect groundwater elevations and flow directions. Continuous recording and quarterly measurements have shown that the aquifer responds quickly to short-term fluctuations in river stages that arise from tidal influences and to longer term fluctuations that arise from changes in flow releases from the dam system on the Columbia River upstream of the facility. As discussed in the *Preliminary Conceptual Hydrogeologic Model*, staff gauge measurements near the facility indicate that the Sandy River stage in the reach immediately east of the RMC facility is controlled by (and similar to) the Columbia River stage (CH2M HILL, March 21, 1996). A comparison of these stages is shown in Table 1-7.

Pumping influences on groundwater levels were also observed during the 26-day Fairview Farms aquifer test. The test was significant because the magnitude of pumping was substantially greater than had occurred to date and because pumping occurred at both the RMC site and at Fairview Farms. The pumping influences were greatest in the deep sand zone but were also observed in the intermediate sand zone.

The influences of river stages and pumping that were observed before and during the Fairview Farms aquifer test are discussed below, with the aid of groundwater elevation contour maps and hydrographs of water level elevations and vertical gradients. The test is described in Appendix A.

1.4.2.1 Groundwater Elevation Contour Maps

Figures 1-14, 1-15, 1-16, and 1-17 show groundwater elevation contour maps for the silt unit, the UGS, the intermediate zone, and the deep zone on August 6, 1997, approximately 29 days before the Fairview Farms aquifer test (which began on September 4). The maps show a generally southeast-to-northwest flow direction in each of the four units, with a groundwater divide extending from the southeastern corner of the site northward towards Company Lake. The maps also show localized variations in the flow direction, including a mound in the UGS near the bakehouse and a cone of depression in the deep zone around production wells PW07 and PW08 and monitoring well MW33-165. This cone of depression was associated with a pumping rate of approximately 450 gpm [0.63 million gallons per day (mgd)] from PW07.

Figures 1-18 and 1-19 show groundwater elevation contours for the intermediate and deep sands, respectively, on September 9, 1997. The maps were constructed using data associated with a low Columbia River stage of 5.06 feet that was measured by the river datalogger at 7:00 p.m. This low stage was the lowest observed throughout the 26-day Fairview Farms aquifer test and was also lower than the stages observed during the week before the test. The groundwater elevations shown at individual wells are low elevations that were observed that evening (between 7:00 and 11:00 p.m.) in response to a low river stage. At that time, wells PW03 and PW07 had been operating for approximately 5.5 days at average discharge rates of 865 and 780 gpm, respectively (for a total of 1,645 gpm).

Comparison of the intermediate zone contours before pumping (Figure 1-16) and after 5.5 days of pumping (Figure 1-18) shows only slight differences in flow directions, primarily in the western portion of the site. These minor differences are likely the result of differences in river stages between the two periods of time. In contrast, the deep zone contours before the Fairview Farms aquifer test (Figure 1-17) and after 5.5 days of pumping at 1,645 gpm (Figure 1-19) show notable differences in groundwater flow directions. The maps indicate that the primary effect of deep zone pumping was the creation of a substantial hydraulic divide across the interior of the site. This divide is defined by deep sand wells MW27, MW29, MW32, MW28, and MW03 (listed from downgradient to upgradient). At these wells, deep sand water levels were only slightly below the intermediate sand water levels. In contrast, wells farther east (MW21 and MW33) showed deep zone water levels that were from 1.5 to 2.5 feet lower than the intermediate zone water levels.

Figures 1-20 and 1-21 show groundwater elevation contours for the intermediate and deep sands, respectively, on September 18, 1997. These maps show the formation of a pronounced cone of depression in the deep zone around pumping well FF04, as well as a possible cone of depression in the intermediate zone at this well. The deep zone map also shows the presence of the hydraulic divide south of Company Lake, as well as the effect of a relatively high river stage on groundwater flow patterns beneath the lake in the deep zone.

1.4.2.2 Groundwater Elevation and River Stage Hydrographs

Figures 1-22 through 1-30 show hydrographs of groundwater elevations at nine well clusters that were monitored during the Fairview Farms aquifer test. The hydrographs also show the pumping cycles and the differences in groundwater elevations between the wells completed in the intermediate and deep sand zones. Groundwater elevation data that were collected manually are shown with a symbol, while datalogger records are shown without symbols. [See also the legend of each figure to determine whether the data were collected manually (designated as "Hand" in the legend) or using dataloggers (designated as "DL" in the legend).] Each hydrograph also shows the hourly datalogger records for the Columbia River stage, as well as the 24-hour moving average of the river stage and the representation of the river stage during the model calibration effort. The hydrograph legends also indicate the unit in which the well was completed (UGS, intermediate sand, or deep sand).

The hydrographs in Figures 1-22 through 1-30 show the following:

- A river stage influence in the intermediate and deep sand zones is visible at each well cluster location, including upgradient well MW03. This effect is shown as the small hourly fluctuations in groundwater elevations on each hydrograph.
- Each well completed in the deep sand and several of the wells completed in the intermediate sand showed instantaneous responses to the initiation of the aquifer test (on September 4, 1997). This effect is visible as the steepening of the water level decline that was occurring prior to the test. This effect is not the result of a river stage decline because the hourly stage data indicate that the river was generally rising during the first 3 days of the test. In addition, the water level declines at the beginning of the pumping period are steeper than the declines that occurred September 7 - 9, when the 24-hour moving average river stage dropped nearly 2 feet.
- Vertical gradients between the intermediate and deep zones were downward at most locations throughout the duration of the test. Minor upward gradients were observed periodically at the southernmost wells (MW03, MW12, and MW15), but gradients at other site wells were almost consistently downward.
- The vertical gradients were substantially greater at wells MW21, MW27, and MW33 than at the other site wells. These three wells are located along the eastern side of the hydraulic divide that was present during the test. (See Figures 1-19 and 1-21 for the locations of these wells and the hydraulic divide.) At each location, the large vertical gradient between the intermediate and deep zones arises from the lithology and completion depth of the intermediate and deep wells. Specifically, the intermediate wells are completed in sand and the deep wells are completed in or below a cemented gravel layer. [See site-scale geologic cross sections E-E′ and F-F′ (Figures 1-7 and 1-8, respectively).] The large downward hydraulic gradient arises from the permeability contrast between the sand (relatively high permeability) and the cemented gravel (relatively low permeability).

  At other well locations (for example, MW29 and MW32), the vertical gradient between the intermediate and deep zones is smaller because the intermediate and deep zone wells are both completed in a sand layer. In addition, the sand layer is underlain by low-permeability materials (silt, sandy silt, and cemented gravel) that limit the hydraulic response of the sand layer to pumping in deeper zones. [See the well completion depths and lithology at MW29, MW32, and nearby production wells as shown in site-scale geologic cross sections C-C′, D-D′, and E-E′ (Figures 1-6, 1-7, and 1-8, respectively).]
- Significant variations also exist in the vertical gradients and water level trends of the three wells that show the largest vertical gradients (MW21, MW27, and MW33); specifically:
  - The trends at MW33 are interpreted to be primarily the effect of pumping. Specifically, the small hourly fluctuations in the deep well groundwater elevations (MW33-165) indicate that the river stage influence at MW33 is minor.
  - In contrast, the trends at MW21 likely arise from both pumping and river stage influences. Groundwater elevations in the deep well at MW21 (MW21-176) show a pattern that is very similar to the hourly datalogger record, which indicates the

effects of a river stage influence plus a pronounced response to the initiation of the first two pumping cycles. (The first pumping cycle consisted of PW3 and PW7 beginning to pump on September 4, and the second cycle consisted of turning on FF04 on September 18 while continuing to pump PW3 and PW7 steadily.)

- The substantial vertical gradient at MW21 is partially a result of the strong hydraulic connection of the deep zone to the river. It is also partly because of the minimal hydraulic connection between the intermediate zone and the river. Groundwater levels in the intermediate zone are similar to those in the UGS at this well. As shown in cross section J-J′ (which compares the geology and screened intervals at the MW21 and MW27 well locations), the intermediate zone wells at both locations are screened above a gravel unit in a surficial sand that also includes the UGS screened interval.
- The vertical gradient at well MW27 is less than at MW21, even though both wells are situated a similar distance from the river. The hydrographs show that the difference is a result of substantially higher water levels in the deep zone at MW27 than at MW21. The cause of the higher groundwater levels at MW27 could be a result of geologic controls and/or less hydraulic connection between the river and the zone screened by this well. The higher water levels at MW27 do not appear to be the result of recharge from Company Lake, as the groundwater elevations in the UGS and the intermediate zone are similar at both well locations.

1.4.3 River Stage Influences on Shallow Groundwater System

In addition to the river influences that were observed during the Fairview Farms aquifer test, other site data have provided important indications of the mechanisms affecting the response of the shallow groundwater system (in particular, the UGS) to river influences. Figure 1-31 compares continuously recorded river stage data and groundwater elevation data at MW05-025 during the summer of 1994. The figure also shows the 24-hour moving average stage for the river. Figure 1-31 shows that groundwater levels in the well (which is completed in the UGS) showed hourly fluctuations similar to the river stage through approximately July 25, 1994. These fluctuations were in response to tidal influences on the river stage. After that date, the groundwater levels began to show a steady decline without the hourly fluctuations that were occurring in the river. Figure 1-31 indicates that this decline began shortly after the moving average of the river stage dropped below an elevation of 7 feet. The sudden and sustained decline in groundwater levels indicates that the UGS groundwater system at this location became hydraulically disconnected from the river.

A similar pattern of hydraulic connection and disconnection was observed during 1995 at UGS well MW21-012, which is north of the dike. Figure 1-32 shows that during the first 5 days of data collection, the well did not show fluctuations in response to the hourly river stage fluctuations. Beginning just before October 27, the well began responding to the hourly river stage fluctuations because the river stage rose sufficiently to reestablish the hydraulic connection. In this case, the connection was established once the 24-hour moving average stage rose above an elevation of about 7.5 feet.

1.5 Onsite Surface Water Features and Their Interaction with Groundwater

The principal surface water features, shown in Figure 1-33, are the Columbia and Sandy Rivers, Company Lake, East Lake, South Ditch, south wetlands, West Drainage, and Salmon Creek. These features lie north of the dike and in the South Plant area (south of the buildings that contain the primary RMC production facilities). The hydrologic relationships of these features to site groundwater are discussed below.

1.5.1 Surface Water Features North of the Dike

1.5.1.1 Company Lake

The principal surface water feature north of the dike is Company Lake, the wastewater treatment pond that covers an area of approximately 14 acres. The pond is part of the facility's National Pollutant Discharge Elimination System (NPDES)-permitted stormwater and wastewater treatment system and is a naturally occurring surface water feature that was present before the RMC facility was constructed. The water level in Company Lake is maintained at a relatively steady elevation by a Parshall flume that is located along an outfall ditch that flows to the Columbia River. The flume has an elevation of 15.5 feet mean sea level (MSL). During occasional periods of high water in the Columbia River (stages above approximately 20 feet MSL), water flows into Company Lake from the river via the outfall ditch. Staff gauge readings during 1997 indicate that the water level in Company Lake ranged from 15.37 to 16.18 feet (CH2M HILL, June 17, 1998). The elevation of the bed of Company Lake ranges from about sea level in the eastern half of the lake to 10 feet or higher in the western half of the lake (CH2M HILL, March 26, 1997).

The significance of Company Lake to groundwater recharge is indicated by groundwater quality data and leachate tests of cores containing sediments and process residue. The highest fluoride concentrations measured in GeoProbes downgradient of the lake during 1997 ranged from 15.9 to 24.5 milligrams per liter (mg/L), which is comparable to concentrations of 18.2 to 23.2 mg/L that were measured in the leachate tests (CH2M HILL, June 17, 1998).

The significance of Company Lake to groundwater recharge is also indicated by water level data. Figure 1-34 compares the Company Lake stage (the elevation of the Parshall flume) with shallow groundwater elevations in nearby monitoring wells. The hydrographs show that the stage was higher than (and presumably recharging) groundwater for a period of about 16 months (June 1994 through September 1995). Low river flow conditions existed during this period,[4] causing groundwater levels to be consistently lower than the water level in Company Lake. Beginning in October 1995, normal to above-normal precipitation and river flow patterns occurred in the region. This caused seasonality in the relationships

[4] Streamflow data collected at The Dalles Dam by the U.S. Army Corps of Engineers indicate that the mean annual flow of the Columbia River at the dam was 132,800 cubic feet per second (cfs) during water year 1994 (October 1993 through September 1994) and 167,400 cfs during water year 1995 (October 1994 through September 1995). These flow rates are approximately 72 percent and 90 percent of the 30-year mean flow of 184,100 cfs from water years 1968 through 1997. During water year 1996, the mean annual flow was 252,300 cfs, which is 137 percent of the 30-year mean flow. These flow rates do not include flows from tributaries to the Columbia River between The Dalles Dam and the RMC facility (including the Sandy River).

between groundwater elevations and the stage of Company Lake. From December 1995 through May 1996, groundwater levels and river stages varied greatly and were higher than the water level in Company Lake for distinct periods of time (causing groundwater to discharge into the pond). However, there were also distinct periods during these months when the water level in Company Lake was higher than the groundwater elevations and the river stage. During the summer and fall months, groundwater elevations and river stages were consistently lower than the water level in Company Lake, which likely caused groundwater to be recharged by Company Lake.

The bed of Company Lake consists of native sand and silt materials overlain by an approximately 6-inch-thick layer of process residue. Permeability testing of three core samples of the native sediments indicates that the vertical hydraulic conductivity of the native sediment in Company Lake is low. The core samples yielded sediment permeabilities ranging from 1.2×10^{-6} to 1.9×10^{-6} cm/sec (CH2M HILL, December 12, 1997). (These permeabilities are equivalent to 0.0034 to 0.0054 feet/day.) A water balance calculation for Company Lake for the period August 23 through October 20, 1997 (which included the Fairview Farms aquifer test), concluded that groundwater was being recharged by Company Lake at a rate of between approximately 280,000 and 430,000 gallons per day (gpd). It is likely that a portion of this flow was through the bed of Company Lake, with some flow also occurring through the sidewalls, which consist of both native and non-native materials.

1.5.1.2 Former West Company Lake

Figure 1-33 shows the outline of the former West Company Lake. Historical aerial air photos show that West Company Lake was once part of Company Lake but was filled; it is now owned by Gresham Sand and Gravel (GS&G). Dredged materials from the Columbia River have been stockpiled in West Company Lake as part of GS&G operations since 1968. By 1971, the west end of West Company Lake had been filled with dredge spoils. Borings in West Company Lake indicate that the fill material is between 8 and 24 feet thick.

1.5.1.3 East Lake

East Lake lies approximately 600 feet to the east of Company Lake. East Lake is a naturally occurring surface water feature and is not used by RMC. Aerial photographs from the 1930s show that East Lake lies within an abandoned former channel of the Sandy River that once connected East Lake to the river and to Company Lake. Today, East Lake is a shallow depression that contains water only during a portion of the year. During periods of unusually high stage, water from the Sandy River can flow into East Lake. Otherwise, there are no inlets or outlets. Water levels in East Lake are thought to primarily reflect Sandy River/ Columbia River stage elevations but may also represent local groundwater elevations when the regional water table is at its seasonal high elevation.

1.5.2 Surface Water Features in the South Plant Area

The principal onsite surface water features in the South Plant area are South Ditch, south wetlands, and Salmon Creek.

1.5.2.1 South Ditch

The South Ditch is the primary drainage feature in the portion of the RMC site that is south of the flood control dike. As shown in Figure 1-33, South Ditch is divided into an eastern reach and a western reach. The eastern reach is dry during the summer months and collects surface water runoff and groundwater seepage from areas near the dike and north of the east potliner soil and debris area during the winter months. West South Ditch extends from east South Ditch to a pump station located at the western end of the ditch (near the southwest corner of the building housing the potlines. West South Ditch conveys the seasonal flow from east South Ditch, effluent from the sanitary wastewater and process wastewater treatment plants, and groundwater discharged from a system of shallow dewatering wells at the bakehouse. These combined flows are pumped from west South Ditch through an underground pipe into Company Lake as part of the NPDES-permitted wastewater treatment system. Water levels in the ditch are controlled by the pumping station, which is designed to prevent water from rising above an elevation of approximately 15 feet.

East South Ditch is a gaining ditch (that is, it receives recharge from groundwater) during the winter months when groundwater elevations are at their seasonal high levels. The ditch then becomes a losing ditch (that is, it loses surface water to groundwater) for a brief period (approximately 2 to 4 weeks during a typical year) once groundwater levels decline below the ditch bed. During this period, the east South Ditch recharges groundwater until it goes dry. In contrast, the west South Ditch flows year-round. It is a gaining ditch during the winter months and becomes a losing ditch beginning in June or July during a typical year. Detailed discussions of groundwater/surface water interactions at South Ditch are contained in Attachment A of *Technical Memorandum DS No. 18: Data Summary for the Wastewater Discharge Areas Addendum to the RI/FS Work Plan, Part 2* (CH2M HILL, June 17, 1998).

1.5.2.2 South Wetlands

South wetlands is a seasonal surface water feature. It receives direct precipitation, stormwater runoff in the old Salmon Creek channel, and stormwater via a culvert and catch basin that are situated along Graham Road. The water level gradually declines beginning in the spring because of a combination of direct evaporation, plant transpiration, discharge to Salmon Creek, and leakage to underlying groundwater. Leakage to underlying groundwater is believed to be limited, as groundwater elevation contour maps for the silt unit do not indicate the presence of a hydraulic mound beneath the area. This is consistent with observations that the bed of south wetlands is composed of low-permeability, fine-grained materials. These materials allow the wetland to accumulate and retain water throughout the rainy season, which would not occur if the soils allowed for rapid infiltration into underlying groundwater.

1.5.2.3 Salmon Creek

Salmon Creek flows along a portion of the southwest border of the RMC property. The creek conveys stormwater from urban and industrial areas and also collects stormwater from portions of the RMC property. Survey data indicate that the creek has a bed elevation of between 12.6 and 13.1 feet along the reach that lies just west of south wetlands. This elevation is lower than groundwater elevations that have been measured historically in nearby silt unit monitoring wells (particularly MW12, MW18, and MW38). In addition, it has been observed that the creek contains water year-round, but an active current is not readily visible during the summer months. These observations and the water level data together indicate that the creek is gaining during the summer months, receiving groundwater discharge from the silt unit.

SECTION 2

Numerical Model Development

SECTION 2

Numerical Model Development

This section describes the development of the numerical groundwater flow model of the Troutdale site. The flow model is a multi-layer finite-element model of the RMC facility and surrounding areas. The model simulates groundwater flow in the USA and the SGA. It simulates the effects of pumping, precipitation infiltration, and interactions with onsite surface water features (such as South Ditch and Company Lake) and offsite surface water features (such as the Columbia and Sandy Rivers). The model also simulates transient groundwater flow conditions and represents the uppermost portion of the groundwater system (in the silt unit) as a water-table aquifer.

The model was developed from regional and site-specific hydrogeologic information and was calibrated to the Fairview Farms aquifer test and the observed distribution of fluoride in the UGS, the intermediate zone, and the deep zone. This section discusses the modeling objectives and the modeling code that was selected, followed by documentation of the model construction and calibration processes.

2.1 Numerical Modeling Objectives and Code Selection

Four uses of the site-scale flow model were identified at the beginning of the project and were translated into modeling objectives. Each use and objective envisioned that the model would provide a quantitative platform for:

- Supporting risk assessment work. This consists of capture zone analyses to evaluate capture (by existing and future hypothetical wells) of fluoride that is currently present in groundwater.
- Evaluating the effectiveness of various actions to address the presence of fluoride in groundwater. This includes simulating changes in groundwater flow patterns and travel times arising from source remediation scenarios.
- Identifying design requirements for proposed groundwater remedial actions.
- Facilitating analysis and decision-making processes through the use of a tool with visualization capabilities.

On the basis of these objectives, the following necessary capabilities and design characteristics of the model and the modeling software were identified:

- Simulation of the following hydrogeologic features and processes:
  - Pumping of groundwater from the RMC production wells and the Fairview Farms wells
  - Groundwater/surface water exchanges with the Columbia and Sandy Rivers, Company Lake, and the onsite and offsite drainages that are present within the model area

  - Areal recharge from precipitation infiltration
  - Laterally and vertically heterogeneous aquifer properties associated with the unconsolidated sediments overlying the Older Rocks
- Transient simulation capabilities for model calibration, which involved simulating the Fairview Farms aquifer test
- Three-dimensional particle-tracking capabilities

Based on these objectives and desired model characteristics, the software Micro-Fem® (Hemker and Nijsten, 1996) was selected as the modeling code for the site. Micro-Fem is a three-dimensional, finite-element groundwater flow model with three-dimensional particle-tracking capabilities. The model may be used to solve groundwater flow problems for unconfined, semi-confined, or confined aquifer systems. The model simulates steady-state or transient flow conditions in up to 16 aquifers with 16 aquitards. The finite-element mesh may contain as many as 12,500 nodes in each model layer. The model contains several different methods for simulating groundwater/surface water interactions. A detailed description of the design and functionality of the model is presented in Appendix B.

2.2 Numerical Model Construction

This section discusses the construction of the numerical model. Specific topics include:

- The design of the finite-element mesh (particularly the locations of mesh boundaries and the spacing of nodes in the mesh)
- The relationship of the model layers to the site geology and well depths (including the establishment of layer thicknesses)
- The assignment of boundary conditions in the model, including surface water features on and adjacent to the RMC facility
- The assignment of values for hydrogeologic parameters required by the model

2.2.1 Mesh Design

Figure 2-1 shows the finite-element mesh that was constructed for the site-scale groundwater flow model. The mesh encompasses the entire RMC property (including Fairview Farms), as well as the Columbia River, the Sandy River, and the Blue Lake Aquifer. The mesh boundaries were established at substantial distances away from the RMC property boundary to conform to natural hydrogeologic boundaries. The locations of the mesh boundaries and the rationales for their location are summarized below:

- **Northern boundary.** The northern boundary of the mesh is the centerline of the Columbia River. This boundary roughly coincides with the Oregon/Washington state line. The river centerline was selected as the northern boundary because the river is a regional groundwater discharge point. The ambient groundwater flow direction north of the river centerline (in Washington) is from north to south, while the ambient groundwater flow pattern south of the river is generally from south to north.

- **Southern boundary.** The southern boundary is aligned with geologic contacts. The western portion of this boundary follows the northern edge of the Troutdale Sandstone Aquifer, as shown in Figure 2-1. (See also the surficial geology shown in Figure 1-2.) The remainder of this boundary lies along the contact between the USA to the north and the TSA and CU2 to the south. This contact is shown in the regional geologic cross section A-A′ (Figure 1-4).
- **Western boundary.** The western boundary is the western edge of the BLA and also follows the western extent of the TSA outcrop lying along the southwestern edge of the BLA. (See Figure 1-2.) The BLA was included in the mesh because previous work by the City of Portland (Woodward-Clyde, 1997; Roger N. Smith Associates, Inc., 1997) indicates that the BLA is a higher permeability unit than the USA, which borders it to the east.
- **Eastern boundary.** The eastern boundary extends northward from the intersection of the southern model boundary and the western shoreline of the Columbia River (east of the RMC facility). The boundary extends from this intersection north to the river centerline (which is roughly coincident with the state line). This boundary is situated approximately 2 miles east of the Sandy River, which is a local discharge feature for groundwater.

Figure 2-2 shows a close-in view of the portion of the mesh containing the RMC facility. As shown in the figure, the mesh contains nodes and elements that outline and include specific site features. The density of nodes and elements in the mesh is also greater in the area shown in Figure 2-2 than in surrounding areas. The mesh is most dense in the south plant area, which includes three soil and debris areas (south landfill, scrap yard, and east potliner).

Following is a summary of the node spacing (that is, the mesh density) in various portions of the mesh and for site features that are assigned specific nodes in the model:

- South plant area: 50 feet, except 25 feet along the banks and centerline of South Ditch
- West Drainage: 25 feet
- Salmon Creek: 50 feet
- Remainder of RMC facility: 100 feet
- Between COE dike and Sandy and Columbia Rivers: 100 feet, except 50 feet along the perimeter of Company Lake and along the Company Lake outfall
- Sandy River: 100 feet
- BLA, Columbia River, and areas between Columbia River and Sandy River: 400 feet
- Fairview Farms and other areas south and west of RMC facility: 250 feet

In addition to this node arrangement, nodes were placed at specific well locations, including the RMC production wells, clusters of monitoring wells, and locations of piezometers and Geoprobes. A list of these locations is presented in Appendix C.

As indicated in Figures 2-1 and 2-2, Oregon State Plane coordinates were used as the horizontal coordinate system for the model. The reference datums are NAD83 and NAD91. [The vertical datum is the 1929 National Geodetic Vertical Datum (NGVD).]

2.2.2 Layer Design

Figure 2-3 shows the conceptualization of the design for the model's layers. As shown in the figure, the model was constructed using 11 layers. This choice of layering was based on the presence of five principal geologic layers (the silt unit, UGS, intermediate zone, deep zone, and the deep USA/SGA water-bearing zones) and the locations of the screened intervals for the RMC production wells, the Fairview Farms former irrigation wells, and site monitoring wells and piezometers. As shown in Figure 2-3, all but three of the boundaries between the model layers are flat (that is, each boundary has a uniform elevation throughout the model domain). The exceptions are:

- The upper boundary of layer 1, which is the water table surface in the silt unit
- The lower boundary of layer 2, which is the geologic contact between the silt unit and the underlying UGS
- The lower boundary of layer 11, which is the geologic contact between the SGA and the underlying Older Rocks unit

Figure 2-3 shows the following additional aspects of the layering scheme:

- The entire saturated thickness of the USA and the SGA is modeled discretely. No portions of the aquifer are modeled through the use of vertical resistivity terms.[5]
- Site monitoring wells are present in layers 2 through 7 of the model. A list of well coordinates and depths is contained in Appendix D, along with a table summarizing the construction of each monitoring well.
- Production wells PW05, PW08, and PW18 contain open intervals in layers 7 and 9 of the model, while the other RMC production wells and the two Fairview Farms wells (FF04 and FF06) contain open intervals exclusively in layer 9 or deeper layers of the model. Construction information for the production wells is summarized in Appendix D, which also includes a map of the locations of former and existing production wells.
- The Columbia River is present in model layers 1 through 4. Bathymetric data for the Columbia River (COE, 1995) indicate that the central channel of the river is between approximately 50 and 60 feet deep. Adjusting for a typical river stage of 10 feet NGVD, this corresponds to an elevation range of -40 to -50 feet NGVD. Because of the presence of bedrock in the middle of the river channel, the actual elevation at which unconsolidated sediments from the RMC facility extend out into the channel is estimated to be approximately -40 feet NGVD, which is near the base of layer 4 (-45 feet NGVD).

[5] The vertical resistivity parameter in a groundwater flow model is the thickness of a layer that is not being directly modeled, divided by the vertical hydraulic conductivity of that layer. The vertical resistivity has units of days, based on the thickness (feet) divided by the vertical hydraulic conductivity (feet/day). Although no aquifer layers were represented with vertical resistivity terms, values of the vertical resistivity are required by the model between adjoining model layers. Consequently, these parameters were specified using an infinitesimal thickness and vertical hydraulic conductivities for the overlying and underlying active model layers.

- The Sandy River is present in model layers 1 through 3. The elevation of the base of the river is estimated to be at or slightly above sea level, based on a typical stage of 10 feet NGVD near the river's mouth and on observed depths of 8 feet and deeper in the lower reaches of the river. The top of layer 3 is at an elevation of 5 feet NGVD.
- The Company Lake NPDES-permitted wastewater pond is present in model layers 1 through 3. As discussed in Section 1.5.1.1, the base of the pond ranges in elevation from sea level in the eastern half of the pond to 10 feet NGVD or higher in the western half of the pond. Consequently, the bed of the pond is situated at or below the top of layer 3, and the pond is therefore assumed to hydraulically penetrate layer 3 of the model.
- South Ditch, Salmon Creek, and West Drainage are surface drainage features that reside in layer 1 of the model.

2.2.3 Boundary Conditions

Specific boundary conditions were established along the perimeter of the mesh and for onsite and offsite surface water features located within the model domain. Details regarding the assignment of these boundary conditions are presented below, including discussions of parameter values associated with each boundary condition. (Other model parameter values are discussed in Section 2.2.4.)

2.2.3.1 Western Boundary (No-Flow)

The western model boundary was established as a no-flow boundary because the ambient flow direction in the BLA and the underlying SGA in this area is northward towards the river (roughly parallel to the boundary), as discussed by McFarland and Morgan (1996). The use of a no-flow boundary condition along the western limits of the BLA is also appropriate because the model does not simulate pumping of BLA wells.

2.2.3.2 Southern Boundary (Specified-Flow)

Constant rates of groundwater flow into the modeled area were specified along the southern boundary of the model. Initial estimates of groundwater flow rates were specified in the layers and nodes where the SGA is present, using the following published information:

- The elevation of the top of the SGA, which is shown in Plate 4 of Swanson et al. (1993). This information indicates that the top of the SGA lies in layer 7 of the model along the western portion of the southern boundary and rises gradually from layer 7 into layer 5 along the eastern portion of the boundary.
- The hydraulic conductivity of the SGA, which has been reported in previous modeling reports for the area. Maps and tables contained in a report documenting the calibration of a model of the Blue Lake Aquifer (Woodward-Clyde, 1997) indicate that the SGA has a typical hydraulic conductivity of 30 feet/day in this area. A report by S.S. Papadopulos and Associates, Inc. (1991) documenting the East Multnomah County groundwater flow model indicates that the typical hydraulic conductivity of the SGA is on the order of 50 feet/day in this area.

- The hydraulic gradient in the SGA, which was estimated from groundwater elevation contour maps contained in McFarland and Morgan (1996) (0.0007 foot/foot) and in Woodward-Clyde (1997) for layer 7 of the BLA model (0.002 foot/foot).

The rates that were initially specified for the SGA along the southern model boundary were based on the information listed above but were adjusted downward during the course of model calibration (which is described in Section 2.3). In addition, groundwater inflow was initially specified in overlying layers where the TSA and CU2 are present using information from the same published sources of information. However, during the course of model calibration these rates were dramatically reduced to levels that were insignificant compared with the rates in the SGA.

2.2.3.3 Northern and Eastern Boundaries (Specified Head and No-Flow)

The northern and eastern boundaries of the model coincide with the Columbia River. As discussed in Section 2.2.2, the river penetrates the upper four layers of the model. In these layers, the model was assigned a specified head equal to the river stage. For the transient simulations that were performed during calibration, the stage was allowed to vary over time according to the observed fluctuations in the river during the Fairview Farms aquifer test (which was the primary calibration condition). The representation of the river stage is shown in Figures 1-22 through 1-30. In deeper layers, the model boundary was specified as a no-flow boundary, and the model calculated groundwater elevations at all boundary nodes. In each layer, selected nodes were inactivated if the node was present at a lower elevation than the bedrock associated with the Older Rocks unit.

2.2.3.4 Sandy River (Head-Dependent)

The Sandy River was simulated as a head-dependent boundary. No boundary condition was assigned in deeper layers.

The stage of the Sandy River was set equal to the stage of the Columbia River for approximately one mile above its mouth and was allowed to vary over time according to stage fluctuations in the Columbia River. Stages in the remaining upstream reaches were interpolated from the stage in the lower reach and estimated stages along the southern boundary that were based on bed elevation data contained in a flood insurance study (FEMA, 1981). The stages in the upper reaches of the Sandy River were also varied slightly during model calibration based on the observed effects of river stage selection on groundwater flow directions.

Because the river penetrates layers 1 through 3 of the model, a low vertical resistivity value (1 day) was used to create a uniform head distribution through these three model layers. This value is equivalent to a one-foot thick layer of material having a vertical hydraulic conductivity of about 3×10^{-4} cm/sec (1 foot/day).

2.2.3.5 Company Lake (Head-Dependent)

The stage at Company Lake was specified from staff gauge readings. During the Fairview Farms aquifer test, the stage rose from 15.50 feet at the beginning of the test to 15.98 feet at the end of the test. The rise in the stage resulted from discharge of pumped groundwater into Company Lake via west South Ditch.

As with the Sandy River, the vertical resistivity term for Company Lake was set to a uniform value in layers 1 through 3 of the model to reflect the pond's penetration of these three layers. Based on the calibration process described in Section 2.3, the vertical resistivity was set at 50 days in the calibrated model. This value is equivalent to a 6-inch-thick layer of material having a vertical hydraulic conductivity of about 3.5×10^{-6} cm/sec (0.01 foot/day).

2.2.3.6 East Lake (Precipitation Infiltration)

East Lake was dry during the summer of 1997, including during the Fairview Farms aquifer test. As discussed in Section 1.5.1.3, the lake is dry much of the year and receives water from direct precipitation and occasional high flows in the Sandy River. Consequently, precipitation infiltration is the only mechanism by which the lake interacts with groundwater.

2.2.3.7 West South Ditch (Head-Dependent)

A head-dependent boundary was used for west South Ditch because water is continually present due to discharges from the process wastewater and sanitary wastewater treatment systems. The stage in west South Ditch was defined from three staff gauges (SG-03, SG-04, and SG-05) located in this portion of South Ditch. [See Table A1 in Attachment A of *Technical Memorandum DS No. 18: Data Summary of the Wastewater Discharge Areas Addendum to the RI/FS Work Plan, Part 2* (CH2M HILL, June 17, 1998).] Data at staff gauge SG05 (closest to the South Ditch pump station to Company Lake) indicate that the stage was between 19.05 and 19.09 feet NGVD during the test, compared with 18.16 feet before the test.

The vertical resistivity of the ditch bed (1,600 days) was established during calibration and is equivalent to a 5-foot thick bed having a vertical hydraulic conductivity of 10^{-6} cm/sec (0.0025 feet/day).

2.2.3.8 East South Ditch (Precipitation Infiltration)

East South Ditch was assigned a precipitation infiltration boundary condition because it is dry during the summer months (including during the Fairview Farms aquifer test).

2.2.3.9 South Wetlands (Precipitation Infiltration)

South wetlands was assigned a precipitation infiltration boundary condition because it is dry during the summer months (including during the Fairview Farms aquifer test). In addition, little—if any—groundwater from the surficial sand unit discharges to south wetlands during the summer months because the water table drops below the bed of south wetlands. [See Appendix A of the *Draft Groundwater Remedial Investigation Report* (CH2M HILL, in progress) for detailed discussions on groundwater/surface water interactions in the vicinity of south wetlands and other portions of the South Plant area.]

2.2.3.10 Salmon Creek and West Drainage (Drain)

Salmon Creek and West Drainage were assigned a drain boundary condition because water is present in both features year-round, but a moving current is not visible during the summer months (including during the Fairview Farms aquifer test). Survey data in Salmon Creek indicate that the bed of the creek lies at elevation 13.1 feet NGVD at Graham Road and at elevation 12.6 feet downstream at staff gauge SG08 (near the northwestern corner of south wetlands). In comparison, groundwater elevations were above the creek bed at nearby silt unit wells MW18-016 (13.83 feet) and MW38-007 (14.97 feet) on September 2, 1997 (just before the beginning of the Fairview Farms aquifer test). These observations, along with quarterly groundwater elevation contour maps during August 1997 (CH2M HILL, December 18, 1997), indicate that groundwater discharges into these surface water features during the summer months. Although groundwater may be recharged by these drainages at other times, this effect was not observed during the Fairview Farms aquifer test (the time period for model calibration).

The vertical resistivity of the beds of Salmon Creek and West Drainage (400 days) was established during calibration and is equivalent to a 5-foot-thick bed having a vertical hydraulic conductivity of 4×10^{-6} cm/sec (0.01 foot/day).

2.2.4 Assignment of Parameter Values

The primary parameter values requiring specification in the model were:

- Hydrogeologic parameters
  - The saturated thickness of the silt unit, which is defined from the silt unit groundwater elevation and the elevation of the top of the underlying UGS
  - The horizontal hydraulic conductivity, including spatial variations in each model layer
  - The vertical resistivity between each model layer, which required specification of the vertical anisotropy[6] and thickness of each layer (and their variation spatially)
  - The storage coefficient within each model layer
- Aquifer stress parameters
  - The precipitation infiltration rate, which was specified in model layer 1 and varied spatially across the site
  - The stage and the bed resistivity for surface water features represented with specified-head or head-dependent boundary conditions (as discussed in Section 2.2.3)
  - The bed elevation and the bed resistivity for surface water features represented as drains (as discussed in Section 2.2.3)
  - Groundwater flow rates along specified-flow boundaries (as discussed in Section 2.2.3)

The selection of values for parameters other than those discussed in Section 2.2.3 are summarized below.

2.2.4.1 Silt Unit Saturated Thickness

Figure 2-4 shows a contour map of the saturated thickness of the silt unit. The saturated thickness was defined from the elevation of the base of the unit and the water table

[6] The vertical anisotropy is the ratio of the horizontal hydraulic conductivity divided by the vertical conductivity.

elevation measured on September 2, 1997 (two days before the Fairview Farms aquifer test) at wells completed in the silt unit. The base of the silt unit was defined from geologic logs for monitoring wells, production wells, and other exploratory borings. Appendix E contains a detailed listing of the data used to construct the contour map.

2.2.4.2 Horizontal Hydraulic Conductivity

Horizontal hydraulic conductivity values were specified at the beginning of the calibration process from the estimates derived from the sitewide aquifer testing program described in Section 1.4.1. (See the values listed in Tables 1-2 through 1-5 for the silt unit, the UGS, the intermediate zone, and the deep zone.) These values were then varied during the course of the calibration process, as described in Section 2.3. Because the majority of the contacts between model layers are flat, lateral variations in stratigraphy within each model layer were accounted for by differences in the hydraulic conductivity distribution within each layer.

2.2.4.3 Vertical Resistivity Between Model Layers

The vertical resistivity was defined at a given node from the following relationship:

$$c_j = 0.5 * [(b_{j-1} * r_{j-1} / Kh_{j-1}) + (b_j * r_j / Kh_j)]$$

where:

c_j = resistivity of layer j (in units of days)
b = layer thickness (in units of feet)
r = the vertical anisotropy ratio (dimensionless)
Kh = horizontal hydraulic conductivity (in units of feet/day)
j = index for the layer underlying the layer boundary
j-1 = index for the layer overlying the layer boundary

General ranges for values of the vertical anisotropy ratio are available in published literature. Anderson and Woessner (1992) indicate that vertical anisotropy ratios required for modeling applications are generally estimated during the model calibration process and can range from 1:1 to 1:1,000. Walton (1970) indicates that field measurements for most geologic materials range from 1:2 to 1:100. Freeze and Cherry (1979, p. 34) state the following:

> *In the field, it is not uncommon for layered heterogeneity to lead to regional anisotropy values on the order of 100:1 or even larger.*

For the RMC site-scale flow model, the vertical anisotropy was varied throughout the course of the calibration process. This procedure is described in Section 2.3.

2.2.4.4 Storage Coefficients

Storage coefficients were estimated during the calibration process by comparing the response times of simulated and measured groundwater levels to the changes in aquifer stress conditions that occurred during the Fairview Farms aquifer test. Storage coefficients in the final calibrated model were estimated to be on the order of 10^{-3} in the silt unit and the UGS (model layers 1 through 3), 10^{-4} in the intermediate and deep zones (model layers 4 through 7), and 10^{-5} in the SGA (model layers 8 through 11).

2.2.4.5 Precipitation Infiltration

For conditions during September 1997, an initial estimate of 0.1 inch/month was used at the beginning of the calibration process. During calibration, the infiltration rate was raised to 1 inch/month in order to generate sufficiently high groundwater elevations in the silt unit. This rate is approximately one-third of the precipitation recorded during September 1997 (3.09 inches) at a gauge on Division Street that is owned by the City of Portland Bureau of Environmental Services.

2.3 Numerical Model Calibration

The calibration process consisted of a two-part process. The first step consisted of steady-state model runs to establish hydraulic parameters for the silt unit (layers 1 and 2). This was followed by an extensive transient calibration process to establish values of hydraulic parameters (for example, horizontal hydraulic conductivities and vertical anisotropy ratios) for the remaining model layers and the values of other model parameters (for example, stages in the Sandy River, bed resistivities for each surface water feature, and flow rates across specified-flux boundaries). The following sections describe the steady-state calibration process, the transient calibration approach, constraints that were applied to the calibration process, the evolution of the transient calibration process, the attributes of the calibrated model, and the principal conclusions from the transient calibration process. This is followed by particle-tracking analyses (presented in Section 2.4) that were performed at the end of the calibration process to further assess the quality of the calibration.

2.3.1 Steady-State Calibration

The steady-state calibration process consisted of varying the precipitation infiltration rate across the site in order to establish a reasonable groundwater flow pattern in the silt unit and to approximate the elevations that were measured during August 1997. (See Figure 1-14.) As discussed in Section 2.2.4.5, the precipitation infiltration rate was raised from an initial estimate of 0.1 inch/month to a final value of 1.0 inch/month during the steady-state calibration.

The steady-state calibration process was also used to test other aspects of the model's design. Specific observations were:

- The silt unit groundwater flow pattern could not be replicated without specifying a higher areal recharge rate along the south side of the dike (due north of scrap yard and east potliner) than in surrounding areas. A greater amount of vegetative growth and ponded water is present in this area than in other portions of the site. The precipitation infiltration that was estimated from the calibration process was 2 inches/month in this area.
- For the Sandy River, the use of a head-dependent boundary condition was more appropriate than a specified-head boundary condition.
- Groundwater flow patterns in the silt unit in the vicinity of Salmon Creek could not be replicated if the drain boundary condition was inactivated in the model. This suggests that Salmon Creek influences groundwater levels in the silt unit.

2.3.2 Transient Calibration Approach

The transient calibration consisted of performing multiple simulations of the Fairview Farms aquifer test in which simulated aquifer stresses were varied over time. Table 2-1 summarizes the definition of the 23 time steps that were simulated. The stresses that were varied were:

- The rates of pumping from wells PW03, PW07, and FF04
- The stages of the Columbia River as measured by the river datalogger
- The stage of the Sandy River according to variations in precipitation (upper reaches) and the Columbia River stage (lower reaches)
- The stages in South Ditch and Company Lake, which rose because of discharge of pumped groundwater into the ditch (and routing to the lake)

The principal parameters that were varied during the transient calibration process were:

- Horizontal hydraulic conductivity of layers 3 through 11
- Vertical resistivity between model layers for layers 3 through 11, which is a function of the vertical anisotropy ratios and thicknesses of each layer
- Storage coefficients in model layers 1 through 11
- Groundwater inflow rates along the southern model boundary
- Stages and vertical resistivity values in the Sandy River
- Vertical resistivity of the bed of Company Lake

The general goals of the transient calibration process were to match the observed water levels trends during the Fairview Farms aquifer test and to create a model that would be capable of simulating the general distribution of fluoride in groundwater (that is, the locations where fluoride is present above the MCL). The transient calibration of the model was performed using the following sequence of steps:

- **Step 1.** Establishment of hydraulic parameter values in layers 9, 10, and 11 using the observed drawdowns in pumping wells PW03 and PW07. This process consisted of matching the simulated drawdowns in the aquifer formation at each pumping well to one-half of the observed drawdowns in each well (based on an assumed efficiency of 50 percent in each well). Water levels recorded in pumping well FF04 were also considered during this step.
- **Step 2.** Modification of parameter values in layers 3 through 8 of the model, which are the zones overlying the pumping interval (layer 9).

Throughout the transient calibration work, parameter values were selected by considering the contrasts in hydraulic properties of the different aquifer matrix materials (silt, sand, cemented gravel, and uncemented to poorly cemented gravel). Silt and cemented gravel were generally assigned lower horizontal hydraulic conductivities and higher vertical anisotropy ratios than sand or uncemented to poorly cemented gravel. Parameter values were also assigned using lateral and vertical zonation patterns according to lithologic information available from geologic logs for site monitoring and production wells. Parameter values were varied at a broad scale (several hundreds of feet laterally and by layer vertically) according to the configurations of the zonation patterns.

The quality of each simulation that was performed during the transient calibration process was evaluated against the following criteria:

- Time-series plots at 19 well locations:
  - Nested triplet wells at 9 monitoring well locations (MW03, MW06, MW12, MW15, MW21, MW27, MW29, MW32, MW33)
  - Nested paired wells at 4 monitoring well locations (MW18, MW25, MW30, MW31)
  - A single deep monitoring well onsite (MW28)
  - Three single monitoring wells in Fairview Farms (MW35, MW39, MW47)
  - Former irrigation well FF06 (located approximately 140 feet west of FF04)
  - Piezometer FFT01 (located approximately 175 feet southeast of FF04)
  - The general locations of these 19 well locations are as follows:
    - Three well locations are north of Company Lake
    - Three well locations are along the south side of the dike (north of the plant)
    - Three well locations are near RMC's production wells
    - Five onsite well locations are south and west of RMC's production wells
    - Five locations are on the Fairview Farms property
- Groundwater flow directions as indicated by:
  - Groundwater elevation contour maps (Figures 1-14 through 1-21)
  - Fluoride distribution maps [contained in Section 4 of the *Draft Groundwater Remedial Investigation Report* (CH2M HILL, in progress)]
- The understanding of the water budget for the aquifer, with an emphasis on the leakage rate from Company Lake. A water balance analysis for Company Lake during the Fairview Farms aquifer test (CH2M HILL, June 17, 1998) indicated that between 280,000 and 430,000 gpd seeped through the bed of Company Lake into groundwater.

2.3.3 Constraints on the Transient Calibration Process

The following constraints on the transient calibration process were adopted throughout the calibration effort:

- The vertical resistivity through the bed of Company Lake was varied in order to simulate a total leakage rate between 280,000 and 430,000 gpd to groundwater (see Section 2.3.2). Tests were performed to evaluate whether the leakage was occurring primarily from the western portion of Company Lake (near the former West Company Lake).

- The stage in the lower reach of the Sandy River was set equal to the stage in the Columbia River for all time periods as discussed in Section 2.2.3.4.
- The stages in the Columbia River and the lower reach of the Sandy River were specified as a step function defined over periods of hours and days. The simulated stage was specified from the 24-hour moving average of the stage, rather than the instantaneous stage recorded by the river datalogger.
- Permeability contrasts between materials were constrained as follows:
  - Surficial silts and deep silts were specified as less permeable than other materials
  - The UGS was specified as less permeable than the intermediate and deep zones
  - The permeability in layer 10 was constrained to be lower than the permeability of layer 11 because layer 11 is a production zone (unlike layer 10) and has a greater overall gravel content, according to drillers' logs
  - The BLA and CU2 formations were assigned properties from the calibrated model of the BLA (Woodward-Clyde, 1997)
- The vertical anisotropy ratio (the ratio of horizontal to vertical hydraulic conductivity) was constrained as follows:
  - Highest in silts and cemented gravels (~ 100:1, as determined during calibration)
  - Lowest in uniform sands (~ 5:1, as determined during calibration)
  - Other layers in and between these extremes

2.3.4 Evolution of the Transient Calibration Process

The sequence of model parameter adjustments that resulted in the evolution of the calibrated model is summarized below in chronological order.

1. **Storage coefficients.** The storage coefficients were first selected by comparing simulated and measured response times to changes in river stages and pumping. The storage coefficients were concluded to be somewhat higher in the silt unit and the UGS than in the deeper zones. Final storage coefficient values were 10^{-3} in the silt unit and the UGS (model layers 1 through 3), 10^{-4} in the intermediate and deep zones (model layers 4-7), and 10^{-5} in underlying zones (model layers 8 through 11).
2. **Company Lake recharge to groundwater.** The Company Lake bed resistivity was set equal to 50 days, based on a simulated flux of approximately 300,000 gpd through the bed of the lake. This simulated flux is within the estimated range of leakage rates from the water balance analysis (280,000 to 430,000 gpd). Repeated testing was performed to evaluate whether leakage was potentially greater along the western margin of the lake due to placement of dredged fill in the former West Company Lake. The testing indicated that groundwater flow directions in the vicinity of the eastern portion of Company Lake could not be replicated if the leakage rate through the eastern portion of Company Lake is substantially lower than in the western portion.

3. **Groundwater inflow rates along southern model boundary.** Testing was performed on the southern boundary condition to evaluate whether the primary source of water is the SGA or whether overlying layers (specifically, the TSA and CU2) are also important contributors. Repeated simulations indicated that the SGA is a more significant source of water to the model along the southern model boundary than the TSA and CU2. The flux rate in the SGA was specified from the calibrated hydraulic conductivity value for the SGA (50 feet/day) and from a hydraulic gradient value (0.005 feet/foot) equal to one-half the value that was measured from regional water level maps for the area (McFarland and Morgan, 1996).

4. **Aquifer hydraulic parameters in layers 9 through 11.** The horizontal hydraulic conductivity and the vertical anisotropy were established for the SGA gravels in which the production wells are completed (model layers 9 and 11). Values were established in this layer at pumping well locations by simulating drawdowns in the aquifer equal to one-half the measured drawdown of 40 feet recorded in both pumping wells (PW03 and PW07) during the Fairview Farms aquifer test. The hydraulic conductivity values in adjoining areas were then set to the values at the pumping wells, unless geologic data indicated different material types. Repeated simulations were also performed to evaluate whether the selection of hydraulic conductivity and vertical anisotropy terms was resulting in reasonable simulations of the areal extent of the drawdown cones. The horizontal hydraulic conductivity values were established as follows:

   - **Layer 9.** A hydraulic conductivity of 225 feet/day and a vertical anisotropy of 5:1 were established at production wells PW03 and PW07, where layer 9 is composed of well-sorted sands. Elsewhere (including at Fairview Farms well FF04), the hydraulic conductivity value was set equal to 50 feet/day, and the vertical anisotropy was set at 20:1 to reflect the presence of mixtures of sand and gravel lenses. These values also coincide with the values used in the model of the East Multnomah County area (S.S. Papadopulos and Associates, Inc., 1991).

   - **Layer 10.** A hydraulic conductivity value of 50 feet/day and a vertical anisotropy of 20:1 were used throughout most of layer 10, based on simulations that indicated that this layer would need to have a similar permeability as layer 9 in order to not cause excessive drawdown cones in layer 9 and overlying layers.

   - **Layer 11.** The horizontal hydraulic conductivity of layer 11 was set at 100 feet/day, which is approximately one-half the value of the well-sorted sands in layer 9 and about twice the value of the SGA sand and gravel mixtures in layer 10 and portions of layer 9. The vertical anisotropy was selected to be 10:1. Subsequent model simulations indicated that the parameter values in this layer have little effect on the calibration of model layers 1 through 8.

5. **Zonation of horizontal hydraulic conductivity in layers 4 through 7.** The zonation patterns for the horizontal hydraulic conductivity and the vertical anisotropy ratio were established in the model for the intermediate and deep zones (model layers 4 through 7). Subsequent simulations focused on the values of these parameters to assign to each zone in each layer.

6. **Boundary conditions for the Columbia and Sandy Rivers.** Repeated simulations with various sets of horizontal and vertical conductivity values failed to provide reasonable simulations of the observed groundwater flow patterns and the groundwater elevation hydrographs. In particular, groundwater elevations in most layers and across much of the site were consistently a foot or more below the observed elevations. The following three adjustments were made to the model that resulted in improvements to simulated groundwater flow directions and groundwater elevations:

   - **Columbia River boundary condition revision.** The location of the southern shoreline of the Columbia River was redefined at the mouth of the Sandy River. Specifically, the shoreline was relocated northwards to account for the presence of the sandbar at the mouth of the Sandy River. The new shoreline location was placed at the northern edge of the bar, based on a depth sounding map (COE, 1995). The sandbar was assigned the boundary conditions used in the lower reach of the Sandy River.

   - **Relationship of stages in the lower Sandy River and the Sandy River bar to the Columbia River stage.** The stages in the lower reach of the Sandy River and the Sandy River bar were set equal to the stage in the Columbia River after repeated simulations indicated that higher stages caused groundwater flow directions to be consistently inaccurate in the area north of the COE flood control dike. Specifically, the initial model runs simulated groundwater flow in an east-to-west direction beneath and east of Company Lake, whereas the observed groundwater flow direction along the northern side of Company Lake is towards the Columbia River and the mouth of the Sandy River.

   - **Hydrologic role of the upper reaches of the Sandy River.** The upper reaches of the Sandy River were identified as important sources of groundwater recharge, particularly during the period when precipitation resumed in mid-September following the dry season. The parameters describing this effect were continually evaluated throughout the remainder of the calibration process because it was recognized that this source of water was important for improving the simulated groundwater flow directions and groundwater elevations.

7. **Hydraulic properties in layer 4.** Following the revisions to the river boundary conditions, the horizontal and vertical hydraulic conductivity values were assigned to layer 4 (the upper portion of the intermediate zone). The final calibrated values were between those used in layer 3 (the UGS) and layer 5 (the lower portion of the intermediate zone), based on repeated model testing that suggested that hydraulic conductivities within the sands likely increase gradually with depth through these three model layers.

8. **Vertical anisotropy in well-sorted sands.** The vertical anisotropy of the sand horizon within the intermediate and deep zones was established by comparing the measured and simulated differences between the intermediate-zone and deep-zone groundwater elevations that were observed during the Fairview Farms aquifer test. Test simulations suggested that the vertical anisotropy is on the order of 5:1 in the sand horizon, where the intermediate and deep groundwater elevations are virtually identical. In cemented

gravel and silt horizons, the groundwater elevations differ by several tenths of a foot or more, and the vertical anisotropy is estimated to be on the order of 100:1.

9. **Hydraulic properties in layer 3 (the UGS).** The horizontal and vertical hydraulic conductivities of the UGS were the next set of parameters to be defined in the model. A value of 5 feet/day was assigned at south landfill and areas to the west and south of south landfill. A value of 35 feet/day was assigned in the remainder of the model domain.

10. **Hydraulic properties for cemented gravel horizons within the intermediate and deep zones.** The hydraulic relationship of the cemented gravel horizon was evaluated at the beginning of the calibration process and was re-evaluated at this point in the calibration. [This horizon is situated at various depths in the intermediate and deep zones (model layers 4 through 7) at several of the production wells (including PW07 and PW08) and in a broad area north and immediately west of the production wells.] It was concluded that the cemented gravel has about one-tenth the permeability of the well-sorted sands and is only slightly more permeable than the silt horizon. This was determined from repeated testing of the relative permeability relationships, plus the observation that fluoride is present above and absent below the cemented gravels in many portions of the site. Also, earlier model simulations that assumed the permeability of the cemented gravel was as low as the permeability of the silt unit had under-predicted groundwater elevations in the deep zone at four wells where the cemented gravel is present (MW21, MW27, MW29, and MW33). On the basis of multiple test simulations, the horizontal hydraulic conductivity value for the cemented gravel was established at 10 feet/day, and the vertical anisotropy ratio was established at 100:1. The zonation pattern described in item 5, above, was not revised.

11. **Horizontal hydraulic conductivity in well-sorted sands that are present onsite in the intermediate and deep zones.** Next, the horizontal hydraulic conductivity of the sand horizon within the intermediate and deep zones (layers 4 through 7) was raised to a value of 225 feet/day, which is higher than the initial estimates from the aquifer testing program. (See Tables 1-2 through 1-5.) This adjustment was made because initial model runs simulated too much drawdown in these zones. Also, comparisons of particle-tracking tests and fluoride concentration contour maps in the vicinity of the scrap yard indicated that the model was simulating insufficient lateral movement of groundwater in the intermediate zone prior to raising the hydraulic conductivity of the sands.

12. **Horizontal hydraulic conductivity in well-sorted sands that are present west of the RMC plant in the intermediate and deep zones.** The model simulations next focused on the area west of the production wells, including the Fairview Farms property. The simulations to this point had assumed that the horizontal hydraulic conductivity of the intermediate-zone and deep-zone sand in this area was the same as for the sand in the vicinity of the RMC wellfield. However, these model simulations produced insufficient simulated drawdowns in the area west of the RMC wellfield. Further testing of the model suggested that the sand horizon beneath Fairview Farms has a horizontal hydraulic conductivity on the order of 100 feet/day, which is approximately 40 percent of the value for the sand horizon at the RMC wellfield.

13. **Sandy River bed resistivity.** The final calibration step consisted of final adjustments to the vertical resistivity values in the bed of the Sandy River to account for differences between the lower and upper reaches, as well as to account for apparent variations over time in each reach. The purpose of this step was to confirm that changes in the bed resistivity could be made that would improve the remaining discrepancies between simulated and measured groundwater elevations and flow directions. (Consequently, this step was also performed to confirm that no other aquifer parameters needed adjustment.)

    As discussed in Section 1.4.3, groundwater elevation data at wells located near the Sandy River (MW05 and MW21) have historically shown periods when little, if any, hydraulic communication occurs between groundwater and the river. This phenomenon occurs during periods of sustained low river stages, particularly during the summer dry season. In periods before and after the dry season, river stages are sufficiently high to cause hydraulic communication with groundwater. Simulated groundwater elevations at MW21 were too low in the UGS and the intermediate zone throughout much of the calibration process because of a strong simulated hydraulic connection involving groundwater discharge to the Sandy River in this area. The vertical resistivity of the bed was raised upward by a factor of 3 for the first 6 days of the pumping test (that is, for the period from September 4 through September 10) to reduce the simulated groundwater discharge rate into the river and to subsequently raise the simulated groundwater elevations at MW21. This process indicated that the discrepancies in groundwater elevations prior to this step were the result of uncertainties in the Sandy River hydraulic parameters and that further changes to aquifer parameters (hydraulic conductivity, vertical anisotropy, and storage coefficients) were not required. Consequently, the model was considered calibrated, subject to performing particle-tracking analyses (as part of a check of the calibration, as described in Section 2.4).

2.3.5 Description of the Calibrated Model

The calibrated model is described below in terms of the following model aspects:

- The final distribution of aquifer parameters (horizontal hydraulic conductivity values and vertical anisotropy ratios)
- Comparisons of simulated and observed hydrographs of groundwater elevations
- Comparisons of simulated and observed groundwater flow directions

2.3.5.1 Aquifer Parameter Distribution

Figures 2-5, 2-6, and 2-7 show the simulated hydraulic conductivity distribution beneath the RMC facility for the UGS, the intermediate zone, and the deep zone, respectively. Figure 2-8 shows the parameter distribution schematically along the west-east regional geologic cross section A-A′ shown in Figure 1-3. Figure 2-9 shows the parameter distribution schematically along the north-south regional geologic cross section B-B′ shown in Figure 1-4. Key aspects of the hydraulic conductivity distribution are:

- The UGS appears to be more permeable (35 feet/day) north of the COE flood control dike and in the northern and eastern fringes of the RMC facility than in the rest of the modeled area (5 feet/day). This is based on aquifer test results, as well as extensive testing during model calibration. The vertical anisotropy is estimated to be 100:1 for the UGS throughout the model domain.

- Below the UGS, the cemented gravels are somewhat more permeable (10 feet/day) than the silt but are substantially less permeable than the well-sorted sands that are present beneath much of the area. The cemented gravels are estimated to have a vertical anisotropy of 100:1. The highest horizontal hydraulic conductivity (225 feet/day) is associated with well-sorted sands that are also present beneath much of the RMC facility. Well-sorted sands are also present beneath Fairview Farms but are estimated to have a lower hydraulic conductivity (100 feet/day) than onsite. In both areas, the well-sorted sands are estimated to have vertical anisotropy ratios of 5:1.
- In the intermediate and deep zones, the lowest hydraulic conductivity (0.5 foot/day) is associated with the silt horizon that is present in layer 8 at several RMC production wells (for example, PW03, PW07). This layer is also present in layer 9 in the western portion of the RMC facility (for example, at monitoring well MW32).

2.3.5.2 Hydrograph Comparison

As discussed in Section 2.3.2, one of the criteria for assessing the quality of the model during the calibration process was a comparison of measured and simulated groundwater elevations at 19 well locations. Hydrographs of the measured and simulated groundwater elevations at these locations are shown in Figures 2-10 through 2-28. (A hydrograph for pumping well FF04 is included in Figure 2-27.) The hydrographs show that the model simulates groundwater elevations within ¼ to ½ foot of the measured groundwater elevations at most locations throughout the aquifer test.

At some wells, groundwater elevations are over-predicted (that is, are higher than actually measured) during the second and third days of the test (September 6 and 7), most likely because of inherent inaccuracies associated with the discretization of the Columbia River stage during this period. Groundwater elevations also tend to be over-predicted during the last phase of the test (when FF04 had been turned off, but PW03 and PW07 were still running) and during the short recovery period on September 30. Repeated testing of the model suggests that these errors are the result of uncertainties in the definitions of the river stage terms, not the result of the aquifer hydraulic parameters (that is, horizontal hydraulic conductivity and vertical anisotropy). The uncertainties in the definitions of the river stage terms are greatest in the Sandy River, where staff gauge readings are not available and where precipitation events may have caused substantial changes in river stages during the test.

The hydrographs show some locations where groundwater elevations may be over-predicted or under-predicted because of the choice of aquifer parameters. These locations are:

- **MW32.** Groundwater elevations in the UGS are under-predicted (that is, are lower than actually measured) by approximately 1 foot. (See Figure 2-22.) This may be the result of the choice of the horizontal hydraulic conductivity of the UGS, the vertical anisotropy of the UGS, or the vertical anisotropy of the intermediate zone.

- **MW33.** At this well triplet, the groundwater elevations in the UGS and the intermediate zone are under-predicted, and the measured deep zone groundwater elevations lie between the elevations simulated for model layers 6 and 7. (See Figure 2-23.) These disagreements between measured and simulated groundwater elevations may be the result of the choices of the vertical anisotropy ratios in these layers.
- **FFT01 and FF06.** Groundwater elevations at these wells are generally over-predicted. (See Figures 2-27 and 2-28.) However, the simulated drawdowns resulting from turning on FF04 (on September 18) are similar to the measured drawdowns. The discrepancies in groundwater elevations were not further addressed during model calibration because the datalogger records were uncertain (because of possible drifts in the datalogger calibration during the test). This is supported by the observations at monitoring wells MW31 (Figure 2-21) and MW39 (Figure 2-25), which are similar distances from pumping well FF04 and which show a good match between simulated and observed groundwater elevations and drawdowns. Consequently, the hydraulic parameter values that were selected beneath Fairview Farms are considered to be reasonable representations of the aquifer system.

Figure 2-29 shows a hydrograph of the leakage from Company Lake to groundwater during the test. The hydrograph shows that leakage rates fluctuated inversely with changes in the stage of the Columbia River. During the test, the simulated leakage rate ranged from approximately 0.25 to 0.33 mgd (250,000 to 330,000 gpd). This range of leakage rates is within the range of 280,000 to 430,000 gpd estimated from the water balance analysis. (See Section 2.3.2.)

2.3.5.3 Groundwater Flow Direction Comparison

Figure 2-30 shows the groundwater flow direction in the silt unit. The contours show a flow pattern similar to the pattern estimated from field measurements (Figure 1-14). Groundwater flow is generally from south to north. Localized discharge is indicated toward Salmon Creek. Also, a cone of depression is indicated in the eastern portion of the plant facility. The silt unit groundwater elevations and flow directions were generally unchanged during the course of the 26-day Fairview Farms aquifer test.

Figures 2-31 through 2-33 show groundwater elevation contours on September 9, 1997, which was the sixth day of the aquifer test. The figures show groundwater elevation contours for three model layers in which monitoring wells are present sitewide (layers 3, 5, and 7), as well as a fourth layer (layer 9) in which RMC production wells PW03 and PW07 are perforated. On this day, the river stage reached a low average daily value following a continual decline during the first 5 days of the test and the period preceding the test. The groundwater elevation contours and associated flow directions for the intermediate and deep zones (which are most influenced by pumping) generally agree with the field observations presented in Figures 1-18 and 1-19. For the production zone (layer 9 of the model), Figure 2-34 shows that the model simulates a localized cone of depression with groundwater elevations as low as nearly -18 feet NGVD. The contours in Figure 2-34 show the presence of a hydraulic divide beneath the western portion of the RMC facility. The cone of depression extends north of the RMC production wells toward the Sandy and Columbia Rivers, but it extends only a limited distance west of the wells.

Figures 2-35 through 2-38 show groundwater elevation contours in the same four layers at the end of the 15th day of the test (September 18, 1997). At this time, Fairview Farms well FF04 had been operating for 3 hours. Also, the average daily river stage was at the highest level recorded up to that time during the month of September. The figures show that pumping from FF04 had a more dramatic effect on groundwater elevations and flow patterns in the UGS and intermediate zones than pumping from the RMC production wells. The simulated drawdown cone occupying the deep zone (Figure 2-37) and the production zone (Figure 2-38) at FF04 was more radial in shape and more limited in areal extent than at the RMC production wells. The groundwater elevation contours and associated flow directions for the intermediate and deep zones (which are most influenced by pumping) generally agree with the field observations presented in Figures 1-20 and 1-21.

2.3.6 Principal Conclusions from the Transient Calibration Process

The principal conclusions from the transient calibration process and the corresponding adjustments to the conceptual hydrogeologic model are the following:

- Vertical hydraulic gradients between the intermediate and deep zone were predominantly downward throughout the RMC facility and surrounding areas during the Fairview Farms aquifer test, including the period when only wells PW03 and PW07 were operating. Vertical gradients between the silt unit, the UGS, and the intermediate zone are also predominantly downward during both pumping and non-pumping periods.
- Pumping of RMC production wells that are completed in the deep zone or in the upper portion of the SGA causes a prominent cone of depression to form in the deep zone at and north of the RMC production wells. In this area, drawdowns and changes in flow directions are substantial. However, only minor drawdowns and no changes in deep-zone groundwater flow directions are observed west of the RMC production wells because of the presence of low-permeability silt and cemented gravel horizons in this area. Although pumping can cause drawdown in portions of the UGS and the intermediate zone, the magnitudes of drawdown are small, and little if any change in groundwater flow directions occurs.
- The sand horizons that make up the UGS and the intermediate zone become progressively more permeable with depth. The sands in the intermediate and deep zones appear to have similar hydraulic conductivities and very low vertical anisotropy ratios, as indicated by water level trends during the Fairview Farms aquifer test. The sand horizons within the intermediate and deep zones also appear to be less permeable beneath Fairview Farms, based on model calibration analyses of drawdowns in this area during pumping of Fairview Farms well FF04.
- Leakage rates from Company Lake to underlying groundwater during the Fairview Farms aquifer test are estimated to have been between 280,000 and 430,000 gpd from a water balance analysis. The transient calibration process suggested that the leakage rate from Company Lake was on the order of 300,000 gpd. The transient calibration process also indicated that leakage is likely occurring beneath the entire bed and that the western portion of the lake does not contribute the majority of the leakage.

- The stage in the first mile of the Sandy River (above its mouth) is governed by the stage in the Columbia River. This portion of the Sandy River has a seasonal hydraulic connection with groundwater, with little connection occurring during the dry summer months when river stage is low.
- The stages in farther upstream reaches of the Sandy River are governed by precipitation patterns within the watershed of the river. The upper reaches of the Sandy River (south of the RMC facility) are an important source of groundwater to the UGS, intermediate, and deep zones beneath the RMC facility.

2.4 Calibration Check

As a check on the quality of the calibrated model, three-dimensional particle-tracking was performed to evaluate whether the model was capable of simulating the three-dimensional groundwater flow patterns that have resulted in the presence of fluoride in groundwater beneath portions of the RMC facility. As discussed in Section 4 of the *Draft Groundwater Remedial Investigation Report* (CH2M HILL, in progress), fluoride is present in groundwater beneath the site at concentrations exceeding its MCL (4 mg/L). The portion of the groundwater system containing fluoride above the MCL is for the most part restricted to onsite areas, including areas north of the COE flood control dike. A small area of elevated fluoride is present just west and southwest of Company Lake outside the RMC plant boundary. The portion of the fluoride plume that is present in the intermediate and deep zones appears to be centered around the RMC production wells and results from fluoride loading from two principal areas:

- Scrap yard, which is believed to be the primary source of the portion of the plume south of the production wells
- Company Lake, which is believed to be the primary source of the portion of the plume north of the production wells

The site data suggest that the presence of the fluoride plume in the intermediate and deep zones is attributable to the presence of natural downward gradients from the silt unit and the UGS into the intermediate zone at scrap yard and Company Lake, plus the creation of strong downward gradients from the intermediate zone to the deep zone by pumping of the RMC production wells. An additional cause for fluoride migration from scrap yard and Company Lake is that the silt unit is thin at these two locations compared with the other soil and debris areas in the South Plant (south landfill and east potliner).

Particle tracking was performed using the aquifer parameters from the calibrated model and using steady-state groundwater elevations calculated by the model for historical pumping conditions at the site. Because pumping has fluctuated historically, two simulations were performed. The first simulation used pumping rates and locations that represented plant operations from January 1990 through October 1991. During this period, the long-term average pumping rate was 1,800 gpm from wells PW03 (320 gpm), PW07 (580 gpm), PW08 (600 gpm), and PW10 (300 gpm). Because this period represented a period of sustained plant activity (including operation of all five potlines), this simulation was assumed to consider the effects of the maximum historical pumping operations. Because operations were less from 1992 through 1997, it was also decided to simulate a no-pumping scenario (even though limited groundwater uses continued during this period). The purpose of this second simulation was to evaluate how a sustained period of no pumping might explain minor deviations that were observed between the fluoride plume and the historical pumping simulation results.

For both simulations, the stage in the Columbia River and the lowest 1-mile reach of the Sandy River was maintained at 9.5 feet NGVD, which is the highest daily average stage observed during the Fairview Farms aquifer test and is a reasonable approximation of the long-term average annual stage. The precipitation infiltration rate was maintained at the same rates used in the simulation of the Fairview Farms aquifer test. The model was run in steady-state mode for both simulations. The following subsections describe the results of each simulation, including the travel times associated with the groundwater flow paths that were traced in each simulation.

2.4.1 Historical Pumping Simulation

The flow model illustrates how pumping is responsible for the current configuration of the fluoride plume. Figures 2-39 through 2-42 show the simulated groundwater elevation contours and flow directions for the historical pumping simulation. As with the contours for the early portion of the Fairview Farms aquifer test [when only the RMC production wells were operating (Figures 2-31 through 2-34)], the cone of depression resulting from long-term historical pumping of the RMC production wells is most prominent in the deep zone and the layer from which pumping is occurring.

Figure 2-43 shows a legend for maps that show the simulated three-dimensional movement of imaginary particles that were initiated in the model at scrap yard, south landfill, east potliner, MW33, and Company Lake (see Figures 2-44 through 2-48). Each map shows the traces of particles that are initiated at various depths and locations in the model and tracked forward in time to delineate groundwater flow paths. The change in color along the length of a given particle trace illustrates the vertical movement of the particle through the groundwater system. The figures compare the particle traces with the current configuration of the fluoride plumes in groundwater, which are defined by concentrations exceeding the MCL. The figures also compare particle traces under various pumping scenarios for the RMC production wells. Specific observations and conclusions from the figures are as follows:

- Figures 2-44 and 2-45 together suggest that the configuration of the groundwater plume in the intermediate zone south of the RMC production wells is the result of fluoride migration from the scrap yard soil and debris area. For both figures, particles were initiated in the model at the top of the UGS and traced forward in time. Figure 2-44 shows that particles initiated at scrap yard are traced to production well PW08. The figure shows that the existing fluoride plume in the intermediate zone conforms closely in shape to the particle traces between scrap yard and PW08. In contrast, Figure 2-45 shows that the traces of particles initiated at south landfill and east potliner generally lie outside the plume, except where they lie close to the production wells. This is consistent with the understanding that these two soil and debris areas are not primary contributors of fluoride to the intermediate zone.

- Figure 2-46 shows that fluoride that is present in the intermediate and deep zones at MW33 migrates to PW08 under the historical pumping scenario. Groundwater at this location is captured by well PW08 because this well (unlike PW03, PW07, and PW10) has a portion of its perforated interval located within the deep zone.

- Figure 2-47 shows the traces of particles that are initiated at the perimeter of the Company Lake wastewater treatment pond under the long-term average pumping scenario. The traces show that water from the pond recharges groundwater and that groundwater moves radially away from the pond. Particles initiated along the southern and eastern perimeters of the pond are captured by the production wells. In contrast, particles initiated around the remainder of the pond are beyond the zone of influence of the production wells and, therefore, discharge to the Columbia River or the Sandy River bar (which extends into the Columbia River from the mouth of the Sandy River). The particle traces conform well to the presence of fluoride in the UGS and the intermediate zone in areas north of the RMC production wells.[7] However, the traces do not include portions of the intermediate zone fluoride plume lying southwest of Company Lake.

  The presence of fluoride in this area may be attributable to pumping from former production wells PW01 and PW16, which have not operated in many years and were not simulated in the historical pumping run. Also, as shown in the figure, some particles migrate northeast from Company Lake toward the Sandy River but are pulled back towards the RMC production wells rather than discharging to the river. These particles migrate downward into the intermediate and deep zones as they move toward the Sandy River and then into the zone of influence of the production wells. The absence of the fluoride plume in this area suggests that groundwater movement occurs at limited rates that prevent substantial fluoride loading to the intermediate and deep zones along these particle traces.

- The migration of particles from Company Lake toward the production wells indicates that the presence of fluoride in intermediate- and deep-zone groundwater between the pond and the production wells arises from fluoride loading from the pond, rather than migration of fluoride from scrap yard to areas near the pond. This is illustrated in Figure 2-48, which shows the combined particle traces from scrap yard and Company Lake under the long-term average pumping scenario.

2.4.2 No-Pumping Simulation

Figures 2-49 through 2-52 show the simulated groundwater elevation contours and flow directions for the historical pumping simulation. The figures show a northerly to north-westerly groundwater flow direction in all layers. Figures 2-53 through 2-57 show particle traces from the same initial locations as shown in the figures for the historical pumping simulation (Figures 2-44 through 2-48). The primary observations from Figures 2-53 through 2-57 are the following:

- Figure 2-53 shows that groundwater in the UGS along the northern perimeter of scrap yard would migrate toward, and discharge to, the Sandy River under a sustained period

[7] See Section 4 of the *Draft Groundwater Remedial Investigation Report* (CH2M HILL, in progress) for discussions of the nature and extent of fluoride in groundwater beneath the RMC facility.

of no pumping beneath the RMC facility. The particle traces also show that groundwater first migrates into the upper portion of the intermediate zone before eventually migrating back up into the UGS for eventual discharge to the Sandy River.

- Figure 2-54 shows the traces of particles that are initiated at south landfill and east potliner for a no-pumping scenario. The flow paths extending from south landfill are perpendicular to the alignment of the intermediate zone plume of fluoride. These traces and the traces from east potliner both extend in a northeasterly direction, which is perpendicular to the flow direction observed at the site under historical pumping conditions.
- Figure 2-55 shows that groundwater in the intermediate and deep zones at MW33 would migrate toward the Sandy River under a sustained period of no pumping.
- Figures 2-56 and 2-57 show particle migration from Company Lake under the no-pumping scenario. Figure 2-56 shows that particles initiated along the northern side of Company Lake move as they do in the pumping scenario (Figure 2-47). However, particle movement from the southern perimeter of Company Lake is quite different under no-pumping conditions (Figure 2-57) than under pumping conditions (Figure 2-47). Under no-pumping conditions, particles initiated along the southern perimeter move in a northerly direction after migrating into the intermediate zone beneath Company Lake.

As shown in Figures 2-53 through 2-57, the particle traces under the no-pumping scenario lie in generally different areas than the fluoride plumes, particularly south of the COE flood control dike. Consequently, the no-pumping analysis does not describe the minor deviations between the plume configuration and the particle traces for the historical pumping scenario. As discussed previously, the discrepancies may arise from the estimation of pumping rates used in the historical pumping simulation, as well as from former operation of wells that are no longer active or present at the site (particularly PW01 and PW16).

2.4.3 Travel Times

Table 2-2 summarizes groundwater travel times to discharge locations for the flow paths that were shown in the particle trace maps.[8] The table shows the following:

- Groundwater travel times from scrap yard to the production wells (under pumping conditions) are between 10 and 15 years, based on the initiation of particles at the geologic contact between the silt unit and the UGS. In contrast, the travel time is substantially longer under no-pumping conditions. This result is partly attributable to the longer groundwater flow paths under non-pumping conditions. However, it is also partly attributable to increases in groundwater velocities in the UGS, in the intermediate zone, and in the deep zone that arise from pumping of the production wells.

[8] The travel times shown in Table 2-2 are based on an assumption that the effective porosity of the aquifer system is 0.20. Lower effective porosities would decrease the travel times proportionally from those shown in the table.

- Travel times at south landfill under pumping and non-pumping conditions are similar to those at scrap yard. For east potliner, which is located closer to the Sandy River than south landfill and scrap yard, the travel times are similar under pumping and non-pumping conditions although the flow paths and discharge locations are different.

The travel times and discharge points for groundwater at Company Lake vary greatly around the perimeter of the pond under both pumping and non-pumping conditions. For both conditions, travel times are shortest for particles along the north side of the pond, which discharge to the Sandy River and the Sandy River bar over periods of 10 to 15 years. The maximum groundwater travel time to the Columbia River is 30 years under non-pumping conditions, but 60 years under pumping conditions because of enhanced vertical migration caused by sitewide water level drawdown induced by the pumping wells. (See Figures 2-47 and 2-57.) Under pumping conditions, travel times from Company Lake to the production wells are as long as 75 years or more based on the substantial lengths of the groundwater flow paths from the pond to the wells. (See Figure 2-47.)

2.4.4 Conclusions of Calibration Check

In conclusion, the model is capable of simulating the distribution of fluoride in the UGS and the intermediate zones. Minor discrepancies are associated with the variability of historical pumping rates and the associated uncertainties in those rates. The model not only traces the distribution of fluoride laterally and vertically, but also simulates travel times that are sufficiently short with respect to the facility's operating life that they explain the presence of fluoride in site monitoring wells and production wells.

SECTION 3

References

SECTION 3
References

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Tables

Section 1 Tables

Table 1-1
Site-Scale Cross Sections: Objectives and Alignment Selection

Section	Objective	Alignment
C-C'	Section along regional groundwater flow direction	From Ione Reef in Columbia River (northwest) to Troutdale Airport well (southeast)
D-D'	Section along western plant boundary	From Ione Reef (north) to MW12 (south)
E-E'	Section along southern side of flood control dike	From MW31 (west) to MW10 (east)
F-F'	Section along Sandy River's western bank	From MW08 (northwest) to MW10 (southeast)
G-G'	Section through Fairview Farms and just south of plant	From FF06 (west) to Troutdale Airport well (southeast)
H-H'	Section using logs for RMC and Bonneville Power Administration (BPA) production wells north of the potlines	From PW16 (west) to PW08 (east)
J-J'	Compare MW21 and MW27 and estimate layering near Columbia and Sandy Rivers	From west of MW30 to east of MW21

Table 1-2
Statistical Analyses of Silt Unit Hydraulic Test Results

Well #	Well Type	Well Location	Test Type	Analysis Method	Transmissivity (ft^2/min)	Aquifer Thickness (ft)	Estimated Hydraulic Conductivity (ft/min)	Estimated Hydraulic Conductivity (ft/day)	Log 10 Transformation
Slug Tests									
MW11-017	Shallow (silt)	East Potliner	Slug Test	Bower and Rice	0.0035	25	7.1E-05	0.20	-0.70
MW15-024	Shallow (silt)	Perimeter	Slug Test	Bower and Rice	0.0002	25	4.2E-06	0.01	-1.92
MW12-021	Shallow (silt)	Perimeter	Slug Test	Bower and Rice	0.0050	25	1.0E-04	0.29	-0.54
MW03-017	Shallow (silt)	Perimeter	Slug Test	Bower and Rice	0.0300	25	6.1E-04	1.7	0.24
MW05-025	Shallow (silt)	Perimeter	Slug Test	Bower and Rice	0.0350	25	7.1E-04	2.0	0.30
MW06-024	Shallow (silt)	Perimeter	Slug Test	Bower and Rice	0.0750	25	1.5E-03	4.3	0.64
MW02-024	Shallow (silt)	Scrap Yard	Slug Test	Bower and Rice	0.0223	25	4.5E-04	1.3	0.11
MW10-023	Shallow (silt)	South of Dike	Slug Test	Bower and Rice	0.0500	25	1.0E-03	2.9	0.46
MW07-024	Shallow (silt)	South of Dike	Slug Test	Bower and Rice	0.0775	25	1.6E-03	4.5	0.65
MW04-019	Shallow (silt)	South Wetlands	Slug Test	Bower and Rice	0.0011	25	2.3E-05	0.06	-1.19
MW18-016	Shallow (silt)	South Wetlands	Slug Test	Bower and Rice	0.0098	25	2.0E-04	0.56	-0.25
MW17-028	Shallow (silt)	South Wetlands	Slug Test	Bower and Rice	0.0245	25	5.0E-04	1.4	0.15
MW17-016	Shallow (silt)	South Wetlands	Slug Test	Bower and Rice	0.0925	25	1.9E-03	5.3	0.73
							Standard Deviation	**1.83**	**0.79**
							Arithmetic Mean	**1.89**	**-0.10**
	Aquifer Thickness = 25 ft.						**Geometric Mean**	**0.79**	
Possible Outliers									
MW21-012	Shallow (silt)	North Landfill	Slug	Bower and Rice	0.5250	25	1.1E-02	30.24	1.48
MW01-019	Shallow (silt)	Along South Ditch	Slug	Bower and Rice	0.3472	25	7.1E-03	20	1.30

Table 1-3
Statistical Analyses of Upper Gray Sand Hydraulic Test Results

Well #	Well Type	Well Location	Test Type	Analysis Method	Transmissivity (ft^2/min)	Aquifer Thickness (ft)	Estimated Hydraulic Conductivity (ft/min)	Estimated Hydraulic Conductivity (ft/day)	Log10 Transformation
Slug Tests									
MW27-045	Shallow	Adjacent to Company Lake	Slug Test	Bower and Rice	0.6000	50	0.01200	17.28	1.24
MW38-035	Shallow	Along Salmon Creek	Slug Test	Bower and Rice	0.0900	50	0.00180	2.59	0.41
MW32-040	Shallow	Bakehouse	Slug Test	Bower and Rice	0.0600	50	0.00120	1.73	0.24
MW34-038	Shallow	East Potliner	Slug Test	Bower and Rice	0.0900	50	0.00180	2.59	0.41
MW31-034	Shallow	Fairview Farms	Slug Test	Bower and Rice	0.0900	50	0.00180	2.59	0.41
MW30-030	Shallow	Near Gresham Sand and Gravel	Slug Test	Bower and Rice	1.8600	50	0.03720	53.57	1.73
MW21-025	Shallow	North Landfill	Slug Test	Bower and Rice	0.3300	50	6.6E-03	9.50	0.98
MW08-027	Shallow	Perimeter	Slug Test	Bower and Rice	1.7014	50	3.4E-02	49.00	1.69
MW33-033	Shallow	Scrap Yard	Slug Test	Bower and Rice	1.5800	50	0.03160	45.50	1.66
MW29-033	Shallow	South of Dike	Slug Test	Bower and Rice	0.4700	50	0.00940	13.54	1.13
MW37-030	Shallow	South Wetlands	Slug Test	Bower and Rice	0.2300	50	0.00460	6.62	0.82
							Standard Deviation	**20.44**	**0.56**
							Arithmetic Mean	**18.59**	**0.97**
							Geometric Mean	**9.44**	
Short-Term Tests									
MW38-035	Shallow	Along Salmon Creek	Short Term	Confined Thies	0.0520	50	0.00104	**1.4976**	**0.18**
Possible Outliers									
MW35-038	Shallow	East Potliner	Slug Test	Bower and Rice	3.7300	50	0.07460	107.42	2.03
MW09-030	Shallow	North Landfill	Slug Test	Bower and Rice	3.4722	50	6.9E-02	100.00	2.00
MW25-035	Shallow	Scrap Yard	Slug Test	Bower and Rice	0.0013	50	2.6E-05	0.04	-1.43
MW18-031	Shallow	South Wetlands	Slug Test	Bower and Rice	0.0078	50	1.6E-04	0.22	-0.65
MW38-035	Shallow	Along Salmon Creek	Short Term	Recovery	0.0040	50	0.00008	0.1152	-0.94
MW38-035	Shallow	Along Salmon Creek	Short Term	Jacob	0.0240	50	0.00048	0.6912	-0.16

Table 1-4
Statistical Analyses for Intermediate Aquifer Hydraulic Test Results

Well #	Well Type	Well Location	Screened Materials	Test Type	Analysis Method	Transmissivity (ft^2/min)	Aquifer Thickness (ft)	Estimated Hydraulic Conductivity (ft/min)	Estimated Hydraulic Conductivity (ft/day)	Log10 Transformation
Slug Tests										
MW27-081	Intermediate	Adjacent to Company Lake	Sand	Slug Test	Bower and Rice	10.5800	100	0.10580	152.35	2.18
MW32-095	Intermediate	Bakehouse	Sand	Slug Test	Bower and Rice	14.1200	100	0.14120	203.33	2.31
MW31-095	Intermediate	Fairview Farms	Sand	Slug Test	Bower and Rice	8.3000	100	0.08300	119.52	2.08
MW30-100	Intermediate	Near Gresham Sand and Gravel	Sand	Slug Test	Bower and Rice	14.9600	100	0.14960	215.42	2.33
MW21-063	Intermediate	North Landfill	Sand	Slug Test	Bower and Rice	13.1000	100	0.13100	188.64	2.28
MW12-092	Intermediate	Perimeter	Sand	Slug Test	Bower and Rice	7.7000	100	0.07700	110.88	2.04
MW03-098	Intermediate	Perimeter	Sand	Slug Test	Bower and Rice	11.2800	100	0.11280	162.43	2.21
MW15-086	Intermediate	Perimeter	Sand	Slug Test	Bower and Rice	11.5200	100	0.11520	165.89	2.22
MW33-095	Intermediate	Scrap Yard	Sand	Slug Test	Bower and Rice	10.8800	100	0.10880	156.67	2.19
MW06-094	Intermediate	South of Dike	Sand	Slug Test	Bower and Rice	8.3200	100	0.08320	119.81	2.08
MW29-090	Intermediate	South of Dike	Sand	Slug Test	Bower and Rice	11.5200	100	0.11520	165.89	2.22
MW10-090	Intermediate	South of Dike	Sand	Slug Test	Bower and Rice	11.8400	100	0.11840	170.50	2.23
								Standard Deviation	**31.20**	**0.09**
								Arithmetic Mean	**160.94**	**2.20**
								Geometric Mean	**157.81**	
Short-Term Tests										
MW27-081	Intermediate	Adjacent to Company Lake	Sand	Short Term Test	Confined Cooper-Jacob	5.1170	100	0.05117	73.68	1.87
MW27-081	Intermediate	Adjacent to Company Lake	Sand	Short Term Test	Confined Thies Recovery	12.1500	100	0.12150	174.96	2.24
MW27-081	Intermediate	Adjacent to Company Lake	Sand	Short Term Test	Confined Thies	12.8700	100	0.12870	185.33	2.27
MW32-095	Intermediate	Bakehouse	Sand	Short Term Test	Confined Thies	5.9230	100	0.05923	85.29	1.93
MW32-095	Intermediate	Bakehouse	Sand	Short Term Test	Confined Cooper-Jacob	7.8250	100	0.07825	112.68	2.05
MW32-095	Intermediate	Bakehouse	Sand	Short Term Test	Confined Thies Recovery	12.0800	100	0.12080	173.95	2.24
MW06-094	Intermediate	South of Dike	Sand	Short Term Test	Confined Thies Recovery	15.2500	100	0.15250	219.60	2.34
MW06-094	Intermediate	South of Dike	Sand	Short Term Test	Confined Cooper-Jacob	3.0700	100	0.03070	44.21	1.65
MW06-094	Intermediate	South of Dike	Sand	Short Term Test	Confined Thies	3.6700	100	0.03670	52.85	1.72
								Standard Deviation	**61.08**	**0.24**
								Arithmetic Mean	**124.73**	**2.03**
		Aquifer thickness = 100 ft.						**Geometric Mean**	**108.30**	**2.02**
Fairview Farms Aquifer Test										
FFT01	Intermediate	Fairview Farms	Sand	FF04/Datalogger	Recovery Theis	38.1700	300	0.12723	183.22	2.26
FFT01	Intermediate	Fairview Farms	Sand	FF04/Datalogger	Papadopulos-Cooper	38.2900	300	0.12763	183.79	2.26
FFT01	Intermediate	Fairview Farms	Sand	FF04/Datalogger	Confined Cooper Jacob	40.8200	300	0.13607	195.94	2.29
FFT01	Intermediate	Fairview Farms	Sand	FF04/Datalogger	Confined Theis	41.3200	300	0.13773	198.34	2.30
								Standard Deviation	**6.87**	**0.02**
								Arithmetic Mean	**190.32**	**2.28**
								Geometric Mean	**190.20**	**2.28**

Table 1-5
Statistical Analyses of Deep Aquifer Hydraulic Test Results

Well #	Well Type	Well Location	Screened Materials	Test Type	Analysis Method	Transmissivity (ft^2/min)	Aquifer Thickness (ft)	Estimated Hydraulic Conductivity (ft/min)	Estimated Hydraulic Conductivity (ft/day)	Log10 Transformation
Eastern Half of Site										
MW10-165	Deep	South of Dike	Sand	Short Term Test	Confined Theis	2.4600	200	0.01230	18	1.25
MW10-165	Deep	South of Dike	Sand	Short Term Test	Confined Cooper Jacob	5.3440	200	0.02672	38	1.59
MW10-165	Deep	South of Dike	Sand	Short Term Test	Recovery Theis	12.4800	200	0.06240	90	1.95
								Standard Deviation	**30.32**	**0.29**
								Arithmetic Mean	**48.68**	**1.60**
								Geometric Mean	**39.42**	**1.57**
MW21-176	Deep	North Landfill	Sand/Gravel	Slug Test	Bower and Rice	18.8889	200	0.09444	136	2.13
MW10-165	Deep	South of Dike	Sand/Gravel	Slug Test	Bower and Rice	10.9722	200	0.05486	79	1.90
MW33-165	Deep	Scrap Yard	Sand/Gravel	Slug Test	Bower and Rice	17.4800	200	0.08740	126	2.10
								Standard Deviation	**24.83**	**0.10**
								Arithmetic Mean	**113.62**	**2.04**
								Geometric Mean	**110.58**	**2.04**
MW21-176	Deep	North Landfill	Sand/Gravel	PW3&7/Hand/Corrected	Papadopulos-Cooper	8.7850	300	0.02928	42.17	1.62
MW21-176	Deep	North Landfill	Sand/Gravel	PW3&7/Hand/Corrected	Confined Theis	9.0110	300	0.03004	43.25	1.64
MW21-176	Deep	North Landfill	Sand/Gravel	PW3&7/Hand/Corrected	Confined Cooper Jacob	18.8200	300	0.06273	90.34	1.96
MW33-165	Deep	Scrap Yard	Sand/Gravel	PW3&7 DL	Papadopulos-Cooper	44.6700	300	0.14890	214.42	2.33
MW33-165	Deep	Scrap Yard	Sand/Gravel	PW3&7 DL	Confined Theis	45.7800	300	0.15260	219.74	2.34
MW33-165	Deep	Scrap Yard	Sand/Gravel	PW3&7 DL	Confined Cooper Jacob	24.6400	300	0.08213	118.27	2.07
								Standard Deviation	**72.67**	**0.29**
								Arithmetic Mean	**121.36**	**1.99**
								Geometric Mean	**98.59**	**1.97**

Table 1-5
Statistical Analyses of Deep Aquifer Hydraulic Test Results

Well #	Well Type	Well Location	Screened Materials	Test Type	Analysis Method	Transmissivity (ft^2/min)	Aquifer Thickness (ft)	Estimated Hydraulic Conductivity (ft/min)	Estimated Hydraulic Conductivity (ft/day)	Log10 Transformation
Site Center										
MW27-176	Deep	Adjacent to Company Lake	Sand/Gravel	Short Term Test	Recovery Theis	2.1470	200	0.01074	15.458	1.19
MW27-176	Deep	Adjacent to Company Lake	Sand/Gravel	Short Term Test	Confined Theis	4.2340	200	0.02117	30.485	1.48
MW03-175	Deep	Perimeter	Sand	Short Term Test	Confined Cooper Jacob	4.6770	200	0.02339	33.674	1.53
MW03-175	Deep	Perimeter	Sand	Short Term Test	Confined Theis	7.9870	200	0.03994	57.506	1.76
								Standard Deviation	**15.07**	**0.20**
								Arithmetic Mean	**34.28**	**1.49**
								Geometric Mean	**30.91**	**1.48**
MW27-176	Deep	Adjacent to Company Lake	Sand/Gravel	Slug Test	Bower and Rice	20.4167	200	0.10208	147	2.17
MW28-160	Deep	Bakehouse	Sand	Slug Test	Bower and Rice	25.7200	200	0.12860	185	2.27
MW32-165	Deep	Bakehouse	Sand	Slug Test	Bower and Rice	26.6000	200	0.13300	192	2.28
MW03-175	Deep	Perimeter	Sand	Slug Test	Bower and Rice	23.7500	200	0.11875	171	2.23
								Standard Deviation	**17.10**	**0.04**
								Arithmetic Mean	**173.68**	**2.24**
								Geometric Mean	**172.80**	**2.24**
MW28-160	Deep	Bakehouse	Sand	PW3&7 DL	Papadopulos-Cooper	35.3500	300	0.11783	169.68	2.23
MW28-160	Deep	Bakehouse	Sand	PW3&7 DL	Confined Theis	31.4700	300	0.10490	151.06	2.18
MW28-160	Deep	Bakehouse	Sand	PW3&7 DL	Confined Cooper Jacob	23.3400	300	0.07780	112.03	2.05
MW32-165	Deep	Bakehouse	Sand	PW3&7 DL Cor	Papadopulos-Cooper	22.0400	300	0.07347	105.79	2.02
MW32-165	Deep	Bakehouse	Sand	PW3&7 DL Cor	Confined Theis	24.1700	300	0.08057	116.02	2.06
MW32-165	Deep	Bakehouse	Sand	PW3&7 DL Cor	Confined Cooper Jacob	23.1200	300	0.07707	110.98	2.05
MW32-165	Deep	Bakehouse	Sand	FF04/Datalogger	Papadopulos-Cooper	28.8200	300	0.09607	138.34	2.14
MW32-165	Deep	Bake house	Sand	FF04/Datalogger	Confined Theis	25.1100	300	0.08370	120.53	2.08
MW32-165	Deep	Bakehouse	Sand	FF04/Datalogger	Confined Cooper Jacob	48.3800	300	0.16127	232.22	2.37
MW03-175	Deep	Perimeter	Sand	FF04/Datalogger	Papadopulos-Cooper	17.3300	300	0.05777	83.18	1.92
MW03-175	Deep	Perimeter	Sand	FF04/Datalogger	Confined Theis	19.4200	300	0.06473	93.22	1.97
MW03-175	Deep	Perimeter	Sand	PW3&7 DL	Papadopulos-Cooper	37.6200	300	0.12540	180.58	2.26
MW03-175	Deep	Perimeter	Sand	PW3&7 DL	Confined Theis	36.2700	300	0.12090	174.10	2.24
MW03-175	Deep	Perimeter	Sand	PW3&7 DL	Confined Cooper Jacob	24.7000	300	0.08233	118.56	2.07
								Standard Deviation	**39.41**	**0.12**
								Arithmetic Mean	**136.16**	**2.12**
								Geometric Mean	**130.99**	**2.11**

Table 1-5
Statistical Analyses of Deep Aquifer Hydraulic Test Results

Well #	Well Type	Well Location	Screened Materials	Test Type	Analysis Method	Transmissivity (ft^2/min)	Aquifer Thickness (ft)	Estimated Hydraulic Conductivity (ft/min)	Estimated Hydraulic Conductivity (ft/day)	Log10 Transformation
Western Site and Fairview Farms										
MW15-175	Deep	Perimeter	Sand	Slug Test	Bower and Rice	5.4000	200	0.02700	39	1.59
MW12-184	Deep	Perimeter	Sand	Slug Test	Bower and Rice	9.2400	200	0.04620	67	1.82
MW06-176	Deep	South of Dike	Gravel	Slug Test	Bower and Rice	16.7600	200	0.08380	121	2.08
								Standard Deviation	**33.97**	**0.20**
								Arithmetic Mean	**75.36**	**1.83**
								Geometric Mean	**67.83**	**1.82**
FF06	Deep	Fairview Farms	Sand/Gravel	FF04/Datalogger	Papadopulos-Cooper	26.4100	300	0.08803	126.77	2.10
FF06	Deep	Fairview Farms	Sand/Gravel	FF04/Datalogger	Confined Theis	27.5200	300	0.09173	132.10	2.12
FF06	Deep	Fairview Farms	Sand/Gravel	FF04/Datalogger	Confined Cooper Jacob	34.5500	300	0.11517	165.84	2.22
FF04	Deep	Fairview Farms	Gravel in SGA	FF04/Datalogger	Recovery Theis	37.4800	300	0.12493	179.90	2.26
MW12-184	Deep	Perimeter	Sand	FF04/Hand	Papadopulos-Cooper	17.4000	300	0.05800	83.52	1.92
MW12-184	Deep	Perimeter	Sand	FF04/Hand	Confined Theis	19.8400	300	0.06613	95.23	1.98
MW12-184	Deep	Perimeter	Sand	FF04/Hand	Confined Cooper Jacob	29.7500	300	0.09917	142.80	2.15
MW12-184	Deep	Perimeter	Sand	FF04/Hand	Recovery Theis	39.0800	300	0.13027	187.58	2.27
MW15-175	Deep	Perimeter	Sand	FF04/Datalogger	Papadopulos-Cooper	31.0000	300	0.10333	148.80	2.17
MW15-175	Deep	Perimeter	Sand	FF04/Datalogger	Confined Theis	31.2200	300	0.10407	149.86	2.18
MW15-175	Deep	Perimeter	Sand	FF04/Datalogger	Confined Cooper Jacob	29.2200	300	0.09740	140.26	2.15
MW15-175	Deep	Perimeter	Sand	FF04/Datalogger	Recovery Theis	34.3800	300	0.11460	165.02	2.22
MW06-176	Deep	South of Dike	Gravel	FF04/Datalogger	Papadopulos-Cooper	31.6400	300	0.10547	151.87	2.18
MW06-176	Deep	South of Dike	Gravel	FF04/Datalogger	Confined Theis	30.7800	300	0.10260	147.74	2.17
MW06-176	Deep	South of Dike	Gravel	FF04/Datalogger	Confined Cooper Jacob	34.1600	300	0.11387	163.97	2.21
MW06-176	Deep	South of Dike	Gravel	FF04/Datalogger	Recovery Theis	44.2000	300	0.14733	212.16	2.33
								Standard Deviation	**30.90**	**0.10**
								Arithmetic Mean	**149.59**	**2.16**
								Geometric Mean	**146.06**	**2.16**

Table 1-5 Statistical Analyses of Deep Aquifer Hydraulic Test Results										
Well #	Well Type	Well Location	Screened Materials	Test Type	Analysis Method	Transmissivity (ft^2/min)	Aquifer Thickness (ft)	Estimated Hydraulic Conductivity (ft/min)	Estimated Hydraulic Conductivity (ft/day)	Log10 Transformation
Possible Outliers										
FF04	Deep	Fairview Farms	Gravel in SGA	FF04/Datalogger	Papadopulos-Cooper	4.2600	300	0.01420	20.45	1.31
FF04	Deep	Fairview Farms	Gravel in SGA	FF04/Datalogger	Confined Theis	14.4400	300	0.04813	69.31	1.84
FF04	Deep	Fairview Farms	Gravel in SGA	FF04/Datalogger	Confined Cooper Jacob	6.4970	300	0.02166	31.19	1.49
MW27-176	Deep	Adjacent to Company Lake	Gravel	Short Term Test	Confined Cooper Jacob	0.3490	200	0.00175	2.513	0.40
MW32-165	*Deep*	*Bakehouse*	*Sand*	*FF04/Datalogger*	*Recovery Theis*	*56.6500*	300	*0.18883*	271.92	2.43
MW08-169	Deep	Perimeter	Gravel	Short Term Test	Recovery Theis	0.0066	200	0.00003	0.048	-1.32
MW08-169	Deep	Perimeter	Gravel	Short Term Test	Confined Cooper Jacob	0.0910	200	0.00046	0.655	-0.18
MW08-169	Deep	Perimeter	Gravel	Short Term Test	Confined Theis	0.1040	200	0.00052	0.749	-0.13
MW03-175	Deep	Perimeter	Sand	Short Term Test	Recovery Theis	42.1600	200	0.21080	303.552	2.48
MW03-175	Deep	Perimeter	Sand	FF04/Datalogger	Confined Cooper Jacob	75.9500	300	0.25317	364.56	2.56
MW29-179	Deep	South of Dike	Gravel	Slug Test	Bower and Rice	0.4170	200	0.00209	3.00	0.48

Table 1-6
Physical Parameters Data Summary for HSA Soil Samples Collected During Summer 1998

Station ID	Sampling Date	Approx. Depth or Sample interval (ft bgs)	Specific Gravity *(a)*	Organic Matter Content *(b)*: Moisture Content %	Organic Matter Content *(b)*: Organic Content %	Falling Head (Fixed Wall) Test *(c)* *Sand Matrix*: Wet Density (AT) PCF	Dry Density (AT) PCF	Porosity (AT) %	Vertical Hydraulic Conductivity *(e)* cm/sec	Vertical Hydraulic Conductivity *(e)* ft/day	Triaxial (Flexible Wall) Test *(d)* *Silt Matrix*: Wet Density (BT) PCF	Dry Density (BT) PCF	Wet Density (AT) PCF	Dry Density (AT) PCF	Porosity (AT) %	Vertical Hydraulic Conductivity *(e)* cm/sec	Vertical Hydraulic Conductivity *(e)* ft/day	Triaxial Compression Test - Saturation Data *(d)*: Cell Pressure PSI	Back Pressure PSI	B
South Landfill Area																				
SL-SB61-005	*6/23/98*	*6.5 to 7*	*2.68*	*19.1*	*1.0*	*122.7*	*99.5*	*37.1*	*1.6E-03*	*4.5*										
SL-SB61-017	6/23/98	19 to 21	2.77	42.8	2.6						110.9	76.8	118.5	86.9	50.60	9.8E-08	2.8E-04	50	38.0	1.00
SL-SB61-045	6/23/98	45.5 to 46	2.69	20.3	0.7	124.3	101.6	36.21	1.5E-03	4.4										
East Potliner Area																				
EP-SB01-014	6/24/98	14 to 16	2.72	37.3	1.4						119.3	92.8	140.7	112.3	45.39	2.2E-07	6.2E-04	50	38.0	0.99
EP-SB01-040	6/24/98	42 to 42.5	2.69	20.7	0.6	126.4	101.7	39.64	1.5E-03	4.3										
Scrap Yard Area																				
SY-SB10-005	6/24/98	6 to 6.5	2.74	14.4	0.5	127.7	108.5	30.79	5.6E-04	1.6										
SY-SB10-017	6/24/98	21 to 23	2.71	38.6	2.2						114.5	81.6	121.6	89.9	50.81	1.4E-07	3.9E-04	50	38	0.99
SY-SB10-035	6/24/98	39 to 39.5	2.69	21.9	0.7	121.8	95.0	42.87	1.7E-03	4.7										
SY-SB11-005	6/24/98	7 to 9	2.73	41.2	2.1						108.7	77.4	115.8	81.5	54.91	2.0E-06	5.8E-03	60	48	0.97
SY-SB11-040	6/24/98	40.5 to 41	2.71	22.8	0.5	126.8	98.2	45.89	4.2E-03	11.9										

Notes:
(a) Specific gravity by ASTM D 854
(b) Organic Matter Content (Physical) by ASTM D 2974
(c) Permeability Test - Falling Head by COE Method. (AT) = After test
(d) Triaxial, Back Pressure Permeability/Compatibility Testing TX/PBP, ASTM D 5084. (BT) = Before test, (AT) = After test, B = pore pressure parameter = ratio of pore pressure response.
(e) Vertical hydraulic conductivity is average of values from Falling Head Fixed Wall Test and Triaxial, or Flexible Wall Test

ft bgs = feet below ground surface
% = percent
PCF = pounds per cubic foot
PSI = pounds per square inch

Table 1-7
Comparison of Columbia River and Sandy River Surface Water Levels

Date	Columbia River		Sandy River		Difference Between Sandy and Columbia River Levels
	Time	Elevation	Time	Elevation	
7/18/94	10:30	6.23	10:00	6.96	-0.73
7/19/94	10:30	7.18	11:05	7.29	-0.11
7/20/94	8:00	8.18	9:30	8.00	0.18
7/21/94	7:30	8.60	9:10	8.52	0.08
7/25/94	16:00	7.12	15:37	7.34	-0.22
7/26/94	9:00	7.88	8:35	7.82	0.06
7/27/94	10:00	7.54	10:10	7.70	-0.16
7/28/94	9:00	6.54	8:25	6.67	-0.13
7/29/94	9:00	5.81	8:44	6.18	-0.37

Section 2 Tables

Table 2-1
Definition of Time Steps for Transient Calibration Process

TIME DEFINITION							RIVER STAGES			PUMPING
Time Step	Start Time	End Time	Length (minutes)	Length (hr)	Length (days)	Total Days	Columbia River Stage	Upper Sandy River Stage [a]	South Ditch Stage (Staff Gauge SG-05)	Pumping Phase
1	9/4/97 7:56	9/5/97 0:00	964	16.1	0.67	0.67	7.5	10.00	18.16	PW03 / PW07 on
2	9/5/97 0:00	9/7/97 3:00	3060	51	2.13	2.80	7.5	10.00		
3	9/7/97 3:00	9/9/97 0:00	2700	45	1.88	4.67	6.8	10.00		
4	9/9/97 0:00	9/10/97 21:00	2700	45	1.88	6.55	6	10.00	19.08	
5	9/10/97 21:00	9/12/97 0:00	1620	27	1.13	7.67	6.6	10.25		
6	9/12/97 0:00	9/13/97 8:00	1920	32	1.33	9.00	7.2	10.50		
7	9/13/97 8:00	9/15/97 0:00	2400	40	1.67	10.67	6.8	10.25		
8	9/15/97 0:00	9/16/97 14:00	2280	38	1.58	12.25	7.5	10.50	19.09	
9	9/16/97 14:00	9/17/97 6:00	960	16	0.67	12.92	8	10.75		
10	9/17/97 6:00	9/17/97 18:00	720	12	0.50	13.42	8.75	11.00		
11	9/17/97 18:00	9/18/97 2:00	480	8	0.33	13.75	9.25	11.25		
12	9/18/97 2:00	9/18/97 9:00	420	7	0.29	14.05	9.5	11.25		
13	9/18/97 9:00	9/19/97 0:00	900	15	0.63	14.67	9.5	11.25		FF04 on
14	9/19/97 0:00	9/21/97 0:00	2880	48	2.00	16.67	9.5	11.00		
15	9/21/97 0:00	9/22/97 12:00	2160	36	1.50	18.17	9.25	10.75		
16	9/22/97 12:00	9/23/97 8:00	1200	20	0.83	19.00	8.6	10.50		
17	9/23/97 8:00	9/24/97 0:00	960	16	0.67	19.67	8	10.50		
18	9/24/97 0:00	9/24/97 20:00	1200	20	0.83	20.50	8.6	10.75		
19	9/24/97 20:00	9/26/97 9:00	2220	37	1.54	22.05	8.9	11.00	19.05	
20	9/26/97 9:00	9/28/97 0:00	2340	39	1.63	23.67	8.9	11.00		FF04 off
21	9/28/97 0:00	9/29/97 0:00	1440	24	1.00	24.67	8.5	11.00		
22	9/29/97 0:00	9/30/97 1:30	1530	25.5	1.06	25.73	7.5	10.75		
23	9/30/97 1:30	9/30/97 10:15	525	8.8	0.37	26.10	7.2	10.75		PW03 / PW07 off

[a] At the downstream end of the upper reach of the Sandy River. This is near the southern boundary of the RMC facility (near MW03).

Table 2-2
Summary of Estimated Groundwater Travel Times from the South Plant Soil and Debris Areas and Company Lake

Description of Model Run	South Landfill		Scrap Yard		East Pot Liner		Company Lake	
	Particle Destination	Travel Time (years)	Particle Destination	Travel Time (years)	Particle Destination	Travel Time (years)	Particle Destination	Travel Time (years)
Historical Pumping [a, b, c]	PW07 and PW08	10-15	PW08	10-15	PW08	25-30	Sandy River and Sandy River bar	10-20 [d]
							Columbia River	20-60 [e]
							PW03	10-50 [f]
							PW07 and PW08	10-75 or more [g]
No Pumping [b, c]	Sandy River and Sandy River Bar	45-60 (River) 60-80 (Bar)	Sandy River	30-40	Sandy River	20-40	Sandy River and Sandy River bar	10-15 [d] 20-30 [f]
							Columbia River	20-30 [e]

[a] The total pumping rate is 1,800 gpm (2.6 mgd), which is an estimate of the estimated monthly pumping demand when the RMC Troutdale facility is operating at capacity. The pumping is distributed among the wells as follows: 320 gpm at PW03, 580 gpm at PW07, 600 gpm at PW08, and 300 gpm at PW10. For wells PW03 and PW07, all pumping is from a depth interval of approximately 230-260 feet, which is represented by layer 9 of the model. For well PW08, 20 percent of the pumping occurs from the deep zone (model layer 7) and 80 percent occurs from model layer 9. All PW10 pumping occurs from the deep gravel zone beneath the site, which is the deepest model layer (layer 11).

[b] Groundwater travel times shown in the table are based on an effective porosity of 0.20 and on the initiation of particles at the top of the UGS along the perimeter of each soil and debris area. A smaller effective porosity or initiation of the particles deeper in the UGS would shorten the travel times.

[c] The two model runs together indicate the ability of the model to simulate the current distribution of fluoride in groundwater. Neither run by itself provides this indication because of the variability in the historical pumping schedule since the plant began operations.

[d] Particles were initiated along the northern perimeter of the lake.

[e] Particles were initiated along the western and southwestern perimeters of the lake.

[f] Particles were initiated along the southern perimeter of the lake.

[g] Particles were initiated along the eastern portion of the northern lake perimeter.

Appendix A

Fairview Farms Aquifer Test

APPENDIX A

Fairview Farms Aquifer Test

A 26-day aquifer test was conducted during September 1997 at two RMC production wells and a former irrigation well (FF04) on the Fairview Farms property. The test consisted of five phases of pumping, which are listed in Table A-1 along with the pumping rates at individual wells and the combined pumping rate. As discussed in the *Memorandum WP No. 36: Proposed 1997 Groundwater Work Plan* (CH2M HILL, June 5, 1997), the purpose of the test was to collect hydraulic response data under a greater aquifer stress condition (higher pumping rates for a longer duration) than had been created previously. An additional objective of the test was to evaluate the effects of pumping simultaneously on the Fairview Farms property and from the RMC production wells.

As shown in Table A-1, the pumping rate was 1,635 gpm during Phases 1 and 3 of the test and 2,630 gpm during Phase 2 of the test. By design, the condition of increased stress was established in Phase 2, when FF04 was operating.[1] Although the rate during Phase 2 was slightly lower than during the 1995 test, the Phase 2 pumping condition was more representative of a high stress condition because:

- Phase 2 involved pumping on the Fairview Farms property, whereas no pumping occurred on that property during 1995
- Phase 2 lasted for 8 full days (versus 58.5 hours of pumping during the 1995 test)

Water levels were monitored throughout each phase of the test at numerous site wells, in the pumping wells, and in two wells west of Fairview Farms well FF04. Continuous recording was performed in Fairview Farms well FF06, which lies approximately 1,700 feet west of FF04. Manual water level measurements were also conducted at observation well PWB-5, which is owned by the City of Portland and which lies approximately 3,500 feet southwest of FF06 and 4,800 feet southwest of FF04.

[1] Phases 1 and 3 were periods in which steady-state pumping of onsite wells PW03 and PW07 was performed in order to supply the water needs of the plant while simultaneously allowing onsite groundwater levels to stabilize with respect to pumping.

TABLE A-1
Summary of Pumping Phases for Fairview Farms No. 4 Aquifer Test
Reynolds Metals Company (Troutdale, Oregon)

Pumping Phase	Start Date (Time)	End Date (Time)	Duration	Pumping Wells and Rates	Combined Pumping Rate
1 (Onsite Wells)	9/4/97 (0750)	9/18/97 (0900)	14 days + 1.2 hours	PW03 (780 gpm) PW07 (865 gpm)	1,635 gpm
2 (Onsite + Offsite Wells)	9/18/97 (0900)	9/26/97 (0900)	8 days	PW03 (780 gpm) PW07 (865 gpm) FF04 (995 gpm)	2,630 gpm
3 (Onsite Wells)	9/26/97 (0900)	9/30/97 (0130)	3 days + 16.5 hours	PW03 (780 gpm) PW07 (865 gpm)	1,635 gpm
4 (Recovery)	9/30/97 (0130)	9/30/97 (1015)	8.75 hours	None (0 gpm)	0 gpm
5 (Normal On-Demand Operations)	9/30/97 (1015)	---	---	---	---

Note: gpm = gallons per minute

APPENDIX B

Description of Micro-Fem® Groundwater Flow Model

APPENDIX B

Description of Micro-Fem® Groundwater Flow Model

General Description

Micro-Fem® (Hemker and Nijsten, Version 3.0, 1996) is a multi-layer, finite-element numerical groundwater flow model. The model is based on software written for a regional groundwater research project conducted in the western part of Holland during 1986 and 1987. The model may be used to solve groundwater flow problems for unconfined, semi-confined, or confined aquifer systems. The model simulates steady-state or transient flow conditions in up to 16 aquifers with 16 aquitards. The finite-element mesh may contain as many as 12,500 nodes in each model layer. The large number of aquifers, aquitards, and nodes is useful when modeling three-dimensional flow features, such as multi-layered aquifers, partially penetrating wells, and aquitard storage.

Model Limitations

As with all groundwater flow modeling codes, general assumptions are made about aquifer conditions and stresses. The following major assumptions are inherent to Micro-Fem:

- For steady-state simulations, the aquifer is assumed to be isotropic in the horizontal plane. Horizontal anisotropy may be specified for transient simulations. Both the steady-state and transient simulation packages allow for specification of vertical anisotropy in multi-layer models.
- Groundwater flow in each layer is horizontal.
- Pumping wells fully penetrate their assigned layers.
- Wells are assumed to pull water from adjacent node areas with 100 percent efficiency.
- Any storage changes that may occur within an aquitard are instantaneous if the aquitard is not being simulated as an active flow layer.

Modules

The model consists of a series of modules that perform distinct functions. The modules are as follows:

- FemGrid: A finite-element grid generator
- FemMesh: A mesh generator for large spacing contrasts
- FeModel: A preprocessor and post-processor

- FemCalc: A steady-state solution algorithm
- FemCat: A transient flow calculation program that includes packages for simulating a variety of surface water/groundwater interactions, evapotranspiration, and head-dependent variable transmissivity (for unconfined aquifers)
- FemInvs: An inverse module for autocalibration
- F3Model: A steady-state, three-dimensional, particle-tracking program
- FemPath: A revision of F3Model that adds forward transient particle-tracking capabilities
- FeMerge: A program for merging model data sets from an existing mesh to a new mesh
- FemBaln: A utility for summarizing water budgets for the entire domain and subareas
- FemProf: A utility for drawing flow lines in profile view
- FemCurv: A utility to draw time-variant results
- FemPlot: A plotting program that includes DXF-file generation capabilities

Each module has been compiled with Borland Pascal (Version 7.0). Each module runs in the DOS environment and can be run in a DOS real mode window under Windows®. A Windows version of Micro-Fem is anticipated to be released during 1999.

Model Construction

Model construction consists of mesh construction and model construction. The model construction step includes specification of boundary conditions, specification of input parameter values and their spatial distribution, and the associated use of model features to perform quality control checks on (and track changes to) the model.

Mesh Generation (FemGrid, FemMesh)

Mesh construction is accomplished using either the FemGrid or the FemMesh module. The mesh may be regularly or variably spaced. The mesh is constructed by specifying fixed nodes around the model boundary and within subregions of the model area; defining line segments between each pair of nodes (to give the generator knowledge of the relationships between fixed nodes and external and internal boundaries); and specifying node separation distances along each line segment (to allow variable mesh spacing). After the mesh is generated, the locations of all nodes except fixed nodes can be moved as needed, although the aspect ratio (the ratio of maximum to minimum dimensions for a given element) should be maintained as close to unity as possible.

Model Construction / Data Importation and Management (FeModel)

This section discusses boundary conditions, parameter specification, and the graphics display features and other model features that facilitate model construction and associated data management tasks.

Boundary Conditions

Outer model boundaries and internal boundaries may be specified head, specified flux, or no-flow boundaries. FeModel allows quick conversions between boundary types, as well as quick conversions between fixed-head nodes and variable-head nodes. Water-balance routines programmed into the FeModel and FemBaln program modules allow quick checks of water balances across specified head boundaries. For transient simulations, the model allows the user to change the head values for specified head boundaries from one time step to the next.

In addition, the model includes simulation packages for top-system boundaries representing evapotranspiration and a variety of surface water features. These are described in further detail below.

Parameter Specification

At each node in the finite-element mesh and for each aquifer layer, the model requires user-specified values of aquifer transmissivity, aquitard vertical resistivity, aquifer recharge and discharge rates, and (for transient simulations) storativity. FeModel employs a zone concept for parameter assignment. Parameter values and zonation patterns may be specified manually or by importing data from ASCII text files, spreadsheets, or from the Grid Utility package contained in SURFER® (Golden Software, 1996). For computations of pathlines in three dimensions, the particle-tracking algorithm (F3Model) also requires specification of the thickness of each aquitard and aquifer, as well as the starting depth of all initialized particles relative to the total thickness of the aquifer in which each particle is initially placed.

The model provides two options for specifying areal recharge. First, areal recharge may be simulated by specifying a fixed recharge rate through a hypothetical recharge well at a given finite-element node. Second, the areal recharge may be simulated as a head of water above the uppermost aquifer layer, with a resistivity term controlling the magnitude of recharge to, or discharge from, the aquifer. This approach allows calculations of head-dependent fluxes and is useful for simulating spatially or temporally variable vertical fluxes and flow directions. This second approach may be deactivated by assigning a value of zero to the resistivity term.

Graphics Display Features and Tracking Capabilities

Four distinctive features of FeModel are its graphic display package; its internalized mathematical functionality; the use of label files to facilitate zonation pattern definitions; and the ability to read, write, and store parameter files and label files into multiple model registers. These features greatly simplify data input and manipulation, facilitate the checking of input parameter values for their accuracy and reasonableness, and facilitate the evaluation of model runs.

- **Display Package.** Full graphics screen control (including a contouring capability) replaces finite-element administration (for example, bookkeeping) and file editing. The contouring capabilities include fill plots, which FeModel generates in a matter of seconds. FeModel can also display DXF files. This can include not only base maps imported from other systems (e.g., AutoCad, ARC/INFO) but DXF maps of model output (e.g., particle flow lines, the model mesh) generated using the FemPlot module.

- **Mathematical Functionality.** The keystrokes associated with parameter specification also allow rapid specifications of parameter values in sub-regions of the model grid area. Parameter values can also be specified by using selected keystrokes together with logical arithmetic commands. This feature is particularly useful for rapid modifications of input parameter sets during sensitivity analyses, as well as for specifying gradual spatial variations in parameter values across subareas of the model. In addition, multiple model registers containing various user-specified data or model-calculated data can be combined mathematically to facilitate evaluation of model results. For example, drawdowns can be calculated and contoured on-screen from registers containing initial heads and model-computed heads.
- **Label Files.** The model data registers that are stored by the FeModel module include a label file register. This register can be used to label nodes according to specific geographic features (including wells) or to help define parameter zones. Because multiple label files can be generated and stored in the model, separate label files can be constructed to designate the zonation patterns for each hydraulic parameter in each model layer. This feature facilitates cross-checking the assignment of parameter values (which are stored in parameter value registers) with the designations in the label files. In addition, the label files can be contoured, which can facilitate quick on-screen identification of zonation patterns and geographic features. Furthermore, such contouring activities can also be conducted in multiple different colors and while viewing DXF base maps on-screen.
- **Parameter and Label File Storage and Transfer.** Numeric data in various model layer registers and alphanumeric data contained in the label file register can be easily written to ASCII text files. Exported parameter files can be written with or without model coordinate information. Extra model layers can also be created and used to store layer elevations, aquifer thicknesses, target heads, or other supplemental data. These layers are then specified as "inactive" during model simulation.

Computational, Particle-Tracking, and Post-Processing Algorithms (All Other Modules)

The model solves nonlinear equations for groundwater flow using an iterative solution technique, with linear basis functions for the horizontal flow components and a finite difference scheme for the flow between adjacent layers. The system of equations is solved iteratively, using the method of successive over-relaxation with automatic adjustment of the relaxation factor. The mesh generation routine is described by Lo (1985). The band-width reduction technique is based on the approach of Gibbs et al. (1976).

Steady-State Models

FemCalc computes steady-state heads in each aquifer layer and uses head and water budget closure criteria to determine when the solution algorithm can be terminated. These closure criteria can be controlled indirectly in command line files during model execution if values other than the default values are desired. The model input file (constructed using FeModel) is overwritten with the newly computed heads in each layer at the end of the simulation. If the modeler wishes to retain initial head values, they may be saved in one-dimensional parameter files that can be readily recalled into subsequent models for comparative purposes.

Presentation of computational results for steady-state models is performed by FeModel and includes water-balance calculations, flow lines within single aquifer layers, flow lines between aquifers, travel times, and contour maps of heads in individual aquifer layers or other parameter values (for example, transmissivity). The keystroke commands and built-in memory registers allow rapid computation of drawdowns and other analyses of interest from computed heads and user-specified input parameter values. FeModel also can be used to perform two-dimensional particle tracking.

The FemInvs module allows for up to 40 parameters to be optimized on the basis of observed hydraulic head data. The results of the optimization routine are additive or multiplicative correction factors for the hydraulic parameters being optimized. The optimization is carried out over a subarea of the model domain.

F3Model and FemPath compute groundwater flow paths in three dimensions. These two packages allow particles to be traced either forward or backward in time.

Any of the graphical model output described above can be saved in DXF format for presentation in other graphics packages. This feature is extremely useful because it allows the user to overlay model results on an appropriate base map (including property boundaries and well locations) for report presentation. DXF files can also be read into FeModel as an overlay to the model grid to facilitate parameter input, grid adjustment, or evaluation of model results.

Transient Models

For transient models, the FemCat solution algorithm is capable of simulating the following conditions:

- A phreatic aquifer with variable transmissivity
- A draining phreatic aquifer
- Directional-dependent resistances between a phreatic aquifer and overlying surface water
- Nonlinear head-dependent drainage systems (for example, extra drainage systems coming into operation when the water table rises above a specified level)
- WADI drainage systems (where the water table is below and hydraulically decoupled from the streambed, and the drainage rate from the streambed to the aquifer is independent of the water table elevation)
- Evapotranspiration from the water table
- Time-variant boundary conditions

For transient simulations, particle tracking is performed using FemPath. Compared with F3Model, FemPath adds the capability of tracing particles forward in time for transient simulations. FemPath calculates real transient forward flow lines. However, reverse particle tracking in a transient model can be performed only by treating the transient model as a series of successive steady-state flow simulations.

Other post-processing capabilities are available through FeModel or FemCurv.

Additional Sources of Information

Attachment 1 contains a two-page fact sheet of the original release of Version 3. Model enhancements have continued since the original release of Version 3, including the release of the FemPath module. A Windows® version of the model is currently in the preparation and testing phases.

Additional information about the Micro-Fem model can be obtained from the World Wide Web at http://www.xs4all.nl/~microfem or by sending an e-mail message to microfem@xs4all.nl . A freeware version (Micro-Fem 3.1 LT) is available from the Web site. The freeware version is limited to two aquifer layers and 2,500 nodes per layer (compared with 16 layers and 12,500 nodes per layer for the retail version of Micro-Fem).

An independent review and test of the Micro-Fem model was presented in the September-October 1997 issue of *Ground Water* (Diodato, 1997). The article is contained in Attachment 2. A full description of the test problem described by Diodato (1997) is also available on the World Wide Web at http://www.ems.psu.edu/Hydrogeologist/spotlight.htm.

References

Diodato, D.M. 1997. "Software Spotlight." *Ground Water* 35(5): 922-923.

Gibbs, N.E., W.G. Poole, and P.R. Stockmeyer. 1976. "An Algorithm for Reducing the Bandwidth and Profile of a Sparse Matrix." *SIAM Journal of Numerical Analysis* 13(2): 236-249.

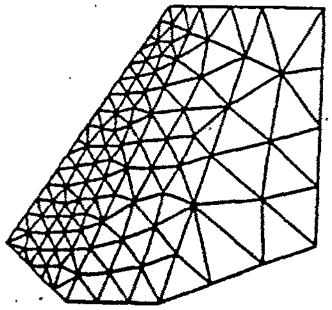
Golden Software, Inc. August 1996. SURFER for Windows, Version 6. Golden, Colorado.

Hemker, C. J. and G. J. Nijsten. April 1996. Micro-Fem, Version 3. Amsterdam, The Netherlands.

Lo, S. H. 1985. "A New Mesh Generation Scheme to Arbitrary Planar Domains." *International Journal of Numerical Methods in Engineering* 21: 1403-1426.

ATTACHMENT 1

Fact Sheet for Original Release of Version 3



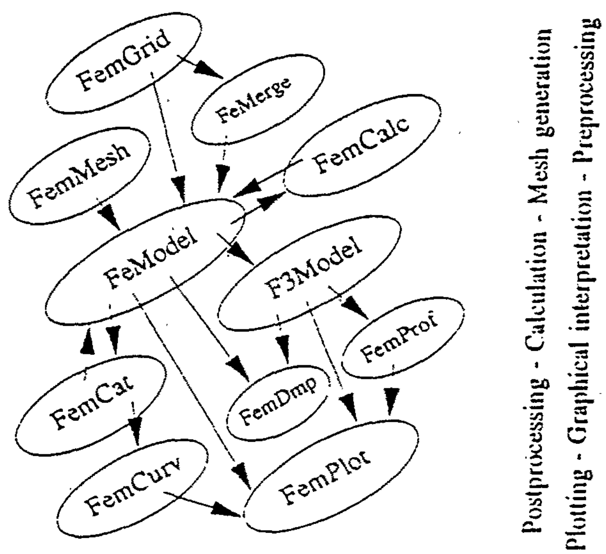
Micro-Fem

an integrated large-capacity finite-element microcomputer program for multiple-aquifer steady-state and transient groundwater flow modeling

Micro-Fem is not a single program; it is a set of eleven programs which takes you through the whole process of groundwater modeling, from the generation of a mesh through the stages of preprocessing, calculation, postprocessing, graphical interpretation and plotting.

General features

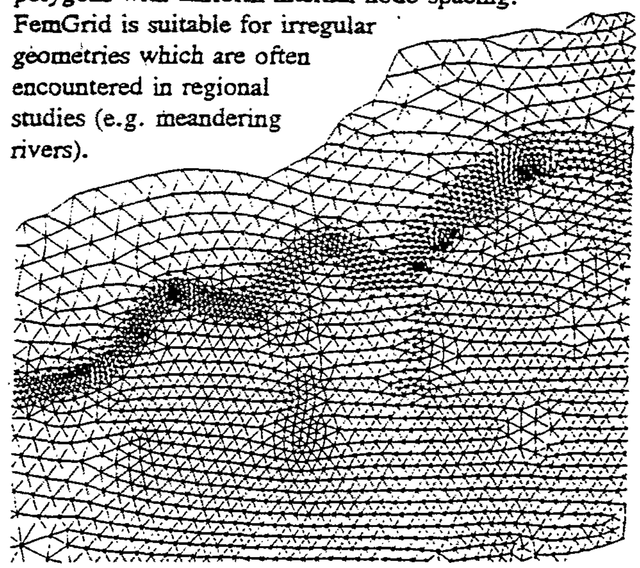
Confined, semi-confined, phreatic, stratified and leaky multiple aquifer systems can be simulated with a maximum of 16 aquifers. The maximum number of nodes is 4000, while the extended memory version handles up to 12500 nodes. No limitations are set to the number of wells. Its capacity, flexibility and ease of use have made Micro-Fem the most widely used groundwater modeling package in the Netherlands. Its users comprise government agencies, consultants and universities.



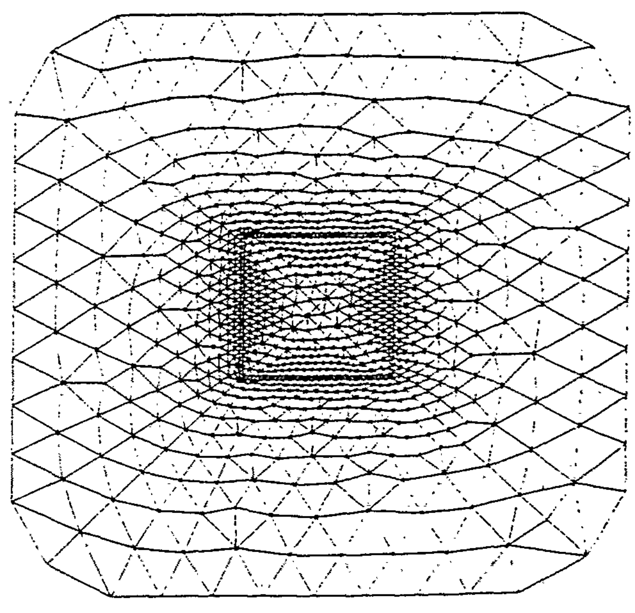
One of the outstanding features of Micro-Fem is the user-friendly graphical interface. Full graphical control makes the otherwise time-consuming and error-prone process of model parameter input easier. The same is true for the interpretation of the results; the visualization of contours, flow-lines, stream vectors, etc. is achieved with just a few keystrokes. It is always possible to make a hardcopy of the results, directly to a printer or a HP-compatible plotter or by saving files in the HPGL or DXF format. The core of Micro-Fem consists of a mesh generator, a fully interactive graphical input/output program and a calculation module.

Finite element grid generation

FemGrid and FemMesh are the mesh generating programs of Micro-Fem. Both make triangular irregular networks with variable spacing. FemGrid generates a mesh based on a subdivision of the area into irregular polygons with uniform internal node-spacing. FemGrid is suitable for irregular geometries which are often encountered in regional studies (e.g. meandering rivers).



FemMesh is based on a subdivision into triangular and quadrangular areas with gradually changing node-spacing. FemMesh is useful for problems which require high contrasts in spacing (e.g. sheet piling, excavations).



Micro-Fem modeling features

- saturated flow, single density
- multiaquifer systems and stratified aquifers
- confined, leaky and unconfined conditions
- steady-state and transient flow
- heterogeneous aquifers and aquitards
- spatially and temporally varying wells and boundary conditions
- spatially varying anisotropic aquifers
- hydraulic heads and water balances
- 2-D and 3-D flowlines with travel times

Calculation

- hybrid finite-element and finite-difference technique
- irregular triangular elements with linear basis functions
- adjustable stop criterions
- any number of stress periods
- SOR (successive over relaxation)
- implicit-explicit and everything in between

Program Features and Capabilities

- graphical user interface
- spreadsheet-like data base interface
- interactive assignment of spatially varying properties
- interactive visual error checking
- up to 16 aquifers or sublayers
- up to 4000 nodes for 640 Kbyte PC
- up to 12500 nodes for EM-version
- mesh generators for regional flow models
- high contrast mesh generator for civil engineering models
- interactive mesh design and adjustment
- user assigned names for all nodes
- areal recharge and any number of wells
- flow vectors and flowlines, 3-D particle tracking
- water balances for each aquifer and subarea
- transferring existing model properties to a new mesh
- transient flow modeling in batch or command mode

Input and Output

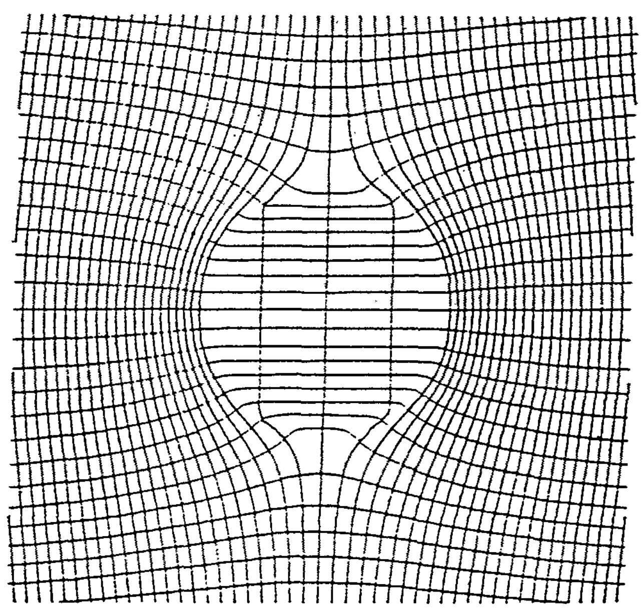
- direct graphical output on screen
- single model file in ASCII format
- plots of grids, contours, flowlines and time series
- true scale screendump program for matrix and laser printers
- Surfer and spreadsheet compatible XYZ-data files
- Auto-CAD compatible files of model data
- HP plotter interactive use
- HPGL file output (plotter, laser printer, word processor)
- DXF file output (GIS and CAD software)
- DXF file input as background map

System Requirements

- IBM-compatible computer
- DOS operating system
- VGA, EGA screen
- color monitor recommended
- coprocessor recommended
- extended memory supported
- one megabyte of hard disk space

Cost, License and Support

- standard package: FemGrid, FemCalc, FeModel, FemPlot and FeMerge: US$ 960
- optional programs:
  FemCat with FemCurv: US$ 450
  F3Model with FemProf: US$ 300
  FemMesh: US$ 300
- includes both PC and EM versions
- no additional charges for shipping, overseas countries, regular update information and disks, etc.
- *extensive user's manual; doc-files on disk*
- reduced version disk available for testing, courses and students: US$ 25
- licence for any number of PC's in customers office
- direct support by fax or mail



Further information and Orders

Send a letter or fax to:

C.J.Hemker, Elandsgracht 83,
1016TR Amsterdam, The Netherlands.
Fax: +31-20.~~[illegible]~~ 6234628

ATTACHMENT 2

Software Spotlight Article from *Ground Water* 35(5): 922-923

SOFTWARE SPOTLIGHT

by David M. Diodato, Pennsylvania State University, Department of Geosciences, 801 Deike Bldg., University Park, PA 16802, e-mail: spotlight@geosc.psu.edu

Introduction

This month's featured package is Micro-Fem v. 3.0, an interactive DOS-based finite-element ground-water modeling package written by C. J. Hemker and G. J. Nijsten. It is an integrated package that includes pre-processor, calculation, post-processor, and graphical modules. It supports simulation of steady-state flow for confined, unconfined, and leaky aquifers. Up to 16 aquifer layers are supported, with up to 12,500 nodes per layer in the extended memory version. A standard set of modules for mesh construction, pre- and post-processing, and graphics is included in the $995 price. Optional modules for transient calculations (FemCat & FemCurv), particle-tracking (FemPath), high-spacing-contrast mesh optimization (FemMesh), and inverse parameter estimation (FemInvs) are also available for prices ranging from $300 to $650. A single purchase includes a license for all personal computers in the purchaser's office. Micro-Fem 3.1 LT is a freeware version of the package which includes all of the Micro-Fem standard and optional modules. The freeware version, which is limited to two aquifer layers and 2500 nodes per layer, is available for download from the Micro-Fem web site.

How We Tested

Micro-Fem requires 2 MB hard drive space and EGA or VGA support. Extended memory and math coprocessor are supported, but not required. We tested Micro-Fem on two Windows 95 (Win 95) machines: a Midwest P166 with a 166 MHz Pentium and 32 MB of RAM; and a Toshiba 410 laptop with a 75 MHz Pentium and 24 MB of RAM. In both cases, Micro-Fem was run in a DOS window of Win 95.

The reviewers implemented and ran a simple test problem of our own design. The test problem is a dolomite aquifer overlain by glacial tills in the eastern region of the model domain and glacial outwash in the central region. A full description of the test problem is available on the world wide web at *http://www.ems.psu.edu/Hydrogeologist/spotlight.htm.* One reviewer had extensive prior experience with Micro-Fem; the other had none. Reviewers spent about 14 hours evaluating Micro-Fem.

What We Found

Micro-Fem is a well-crafted, easy-to-use, and powerful finite-element ground-water modeling package, with over 10 years of development history. The package has a high degree of functionality with minimal hardware resource requirements. Model features worked as billed, and the documentation was well-written. The reviewers received timely responses to e-mail support requests and other questions, even on weekends.

Modeling in Micro-Fem entails: (1) grid generation; (2) model editing and parameterization; (3) calculation of model results; and (4) display or post-processing of results. FemGrid generates grids using triangular elements within user-defined regions. The hierarchical "region-element" approach allows easy user definition of grid geometry. Regions may be defined by keyboard or by ASCII file import (e.g. Surfer .bln files). Different grid spacings may be used in each grid region. We used Surfer .grd files and the Surfer Grid Utility to interpolate known aquifer top and bottom to each of the FemGrid-generated grid nodes. Following automated grid generation, the mesh is automatically optimized to reduce the bandwidth of the connectivity matrix. The user is informed of the node assignments as FemGrid visually "walks" the user through the process. That is very helpful for debugging. FemGrid makes grid generation in Micro-Fem simple and straightforward.

FeModel is Micro-Fem's pre- and post-processing engine. FeModel has four toggled modes: "walking" element/node selection; "entering" data entry; "drawing" graphics; and "alter-grid" to modify the mesh. Each mode uses special keystrokes. Nodes can be added or erased anywhere in the grid. The values of the parameters at the newly added nodes are automatically interpolated from existing nodal values. Node editing functions include addition, deletion, and connection swapping. These performed flawlessly. A simple and fast zoom facility is available—and required—due to the low graphics resolution of the EGA and VGA video modes. Parameters may be examined node-by-node or contoured on screen. This is helpful as a quick way to disclose errors in the input values.

Parameters supported are transmissivity, storativity, constant head, constant flux, and vertical conductance to overlying layers (if any). FeModel employs a zone concept for parameter assignment. Zones are delimited with walking mode keystrokes. Each zone must be manually defined. AutoCAD Drawing Exchange File (.dxf) maps can be imported so that known features (such as geologic contacts) can be traced by "driving" along the map. All parameter files are one-dimensional vectors, so that they are readily created or examined in spreadsheets or Surfer. It is possible to enter labels and parameters for a node, a group of nodes, an area, or the whole model at once. Parameters can be stored in their own model data structures known as registers. The number of registers created is determined by the number of layers the user specifies. Extra layers can be created and used to store aquifer thickness, drawdown, target heads, or other supplemental data. These layers are then specified as "inactive."

Parameter values for a data register may be defined by formula. For example, transmissivity can be input as the product of a hydraulic conductivity field in one data register and a thickness field stored in another. Alternatively, transmissivity can be specified as a function of the distance to a boundary. This is a convenient way to describe an aquifer which pinches out stratigraphically. A wide range of mathematical functions are available in FeModel. This feature is both handy and powerful.

Steady-state head distributions are computed in FeModel. The calculated hydraulic head field is easily visualized by using the built-in contouring capabilities. FemBaln creates water budget files for the entire model area or for specified subareas. For example, all the subsurface flow from the till capped-dolomite to the outwash region can easily be calculated. Transient modeling requires the use of the program FemCat. Hydrographs can be easily produced in the transient packages.

FeModel has a built-in feature that draws flowlines and vectors in a few keystrokes. Flowline files can be saved and converted to .dxf layers in the program FemPlot. Micro-Fem also supports HPGL output. Despite the range of output options available in Micro-Fem, report-ready graphics are best produced by outside graphics packages such as Surfer and Tecplot. Because Micro-Fem outputs x-y-z ASCII data files, it is easy to move data from Micro-Fem to Surfer.

FemPath can calculate either three-dimensional steady-state particle tracks or pathlines based on transient head fields computed by FemCat.

Inverse modeling is supported by the FemInvs module. Inverse modeling allows for up to 40 parameters to be optimized based on observed hydraulic head data. The optimization routine constructs additive or multiplicative correction factors for hydraulic parameters. The optimization is carried out over a subarea of the model domain.

An experienced Micro-Fem user required only about two hours to create the model grid, input the model parameters, make a preliminary run, and make two inverse model runs.

What We Liked

Once the keystroke interface is mastered, the modeling process in Micro-Fem is straightforward. The collection of capabilities in a small yet elegant package is outstanding. Micro-Fem reliably generates and optimizes meshes in a flash, and post-processes a range of output results in an intuitive interactive fashion.

If required, the model grid can be modified interactively from within the program. Very complex patterns can be easily mapped to the grid by "driving" around the grid and marking nodes "en route." Formulae and internal functions are an efficient way to specify input data values. The screen graphics supported by the package were clearly designed to aid the modeler. These allow for easy error-checking of input data and for on-screen visualization of simulation results. The transfer of input and solution data to other programs is not difficult. Transient simulations were easily set up and run. ArcInfo support is outlined in the Appendix to the manual. Sample macros are provided for transferring parameters from ARC-INFO into Micro-Fem, as well as for duplicating the Micro-Fem topology in ARC-INFO. This is a welcome feature.

What We Didn't Like

The FeModel keystroke interface, while articulate, is necessarily clumsy to master due to a high level of context sensitivity. Neither the generally well-written text nor the summary table of keystrokes are, in general, adequate to document context-sensitive command sequences. As a result, model convention familiarization can be painful. More explicit tutorial-style examples of assigning entering or walking mode sequences would have been very helpful. An example is included for FemGrid, but not for FeModel. The interface lacks mouse support. We have come to expect mouse and toolbar alternatives to keystroke commands. Use of color is limited to output results such as contours or vectors. Implementation of user-definable colors for grid zones would improve ease of use for grid zone editing. The VGA video resolution is low, particularly for a model of any complexity. Be prepared to do a lot of "zooming" for large models.

Transient simulation capabilities, a standard part of ground-water modeling, are not included in the standard modules.

Screen-dump graphics did not interrupt the printer port in protected mode. Instead, we needed to use a DOS real mode window under Win 95. Additional software such as Surfer or Tecplot is required to prepare presentation-quality graphics. Some users have written translation routines for porting Micro-Fem output into specialty graphical packages.

Overall

Micro-Fem is an intelligently designed, simple, powerful, and useful modeling package. We were impressed by the capabilities of the software, and by the spartan computer hardware resources required by Micro-Fem.

The reviewers expressed an oft-repeated conundrum—a desire for a more friendly and functional environment while maintaining low hardware resource requirements. While both reviewers liked the highly efficient implementation of Micro-Fem, one wished for a Win 95-style interface and the other desired some enhancement in the ability to prepare report-ready output. A Win 95 version that includes FemCat, FemCurv, and FemPath will be released in 1998. New purchasers of Micro-Fem 3.0 and the optional programs will obtain the Win 95 version free of charge. Existing users may upgrade for $200.

Proficient users of Micro-Fem are able to rapidly assemble and run ground-water models. The cost of the software is not trivial and attaining proficiency requires some time. However, users who have made those commitments will find Micro-Fem to be of value in a broad variety of ground-water modeling endeavors.

Ratings

The reviewers were asked to assign a numerical ranking from 1 (worst) to 5 (best) to the software in the following categories. The reported ranking is the arithmetic mean of the two reviewers' rankings.

Capability	5
Reliability	4.5
Ease-of-Use	3.9
Tech Support	4.5

The Vendor

Micro-Fem is available from C. J. Hemker, Elandsgracht 83, 1016 TR Amsterdam, The Netherlands. Fax: 31-20-6234624, e-mail: *microfem@xs-4all.nl*, web: *http://www.xs4all.nl/~microfem/*.

The Reviewers

The author would like to extend his thanks and appreciation to the individuals who assisted in reviewing this software. They are: Fritz Carlson, CH2M Hill, 2525 Airpark Drive, Redding, CA 96001, *fcarlson@ch2m.com;* and Dr. Joseph Donovan, Department of Geology and Geography, West Virginia University, Morgantown, WV 26506, *donovan@wvugeo.wvnet.edu.*

Our Mission

The goal of *Software Spotlight* is to help you to identify well-written, intuitive software while avoiding poorly written, crash- or error-prone software. Independent reviewers from government, industry, and academia "test drive" full working versions of software packages and provide you with a concise summary of their experiences and opinions regarding the capability, stability, and ease-of-use of these packages. We hope that you find it to be of use to you, and we welcome your comments, feedback, and suggestions for future columns. The best way to give us your input is by e-mail to *spotlight@geosc.psu.edu.*

Appendix C

Well Locations with Fixed Nodes in the Finite-Element Mesh

Appendix C
Groundwater Measurement Stations Represented With Fixed Nodes in the Site-Scale Groundwater Flow Model

Northing (NAD83/NAD91)	Easting (NAD83/NAD91)	Station Name
RMC Monitoring Wells		
694113	7715540	MW01-019
694230	7716768	MW02-034
693409	7716573	MW03-098
694091	7714221	MW04-019
693928	7718662	MW05-025
696082	7713545	MW06-176
695727	7715718	MW07-024
697826	7714040	MW08-169
697248	7715424	MW09-030
695177	7716974	MW10-165
694394	7717692	MW11-017
694269	7713618	MW12-184
694411	7716755	MW13-022
694403	7717247	MW14-015
695058	7713589	MW15-175
693940	7716279	MW16-014
693355	7715611	MW17-028
693637	7714155	MW18-031
693897	7715939	MW19-013
696736	7715342	MW20-026
697207	7715621	MW21-176
696969	7714986	MW22-027
697094	7715126	MW23-025
694320	7716493	MW24-010
694139	7716746	MW25-035
693683	7715907	MW26-012
697221	7713828	MW27-176
694471	7715664	MW28-160
695923	7714523	MW29-179
697377	7712923	MW30-100
696263	7712739	MW31-095
695198	7715477	MW32-165
694936	7716520	MW33-165
694645	7717722	MW34-038
694469	7717571	MW35-038
693711	7714957	MW36-006
693626	7714738	MW37-030
693443	7714083	MW38-035
696094	7711970	MW39-095
694884	7715592	MW40-030
695000	7715460	MW41-033
694863	7715961	MW42-027
694979	7715876	MW43-027
694675	7716131	MW44-027
694415	7715842	MW45-042
694660	7715475	MW46-043
693795	7715894	MW47-094
695182	7715055	MW48-165
694573	7717231	MW49-145
694174	7715123	MW50-094
697752	7712711	MW51-069
697938	7713913	MW52-045
696212	7716997	MW53-034

Appendix C
Groundwater Measurement Stations Represented With Fixed Nodes in the Site-Scale Groundwater Flow Model

Northing (NAD83/NAD91)	Easting (NAD83/NAD91)	Station Name
RMC Production Wells		
695360	7714480	PW01
695378	7715262	PW02
695296	7715678	PW03
695150	7716242	PW04
695350	7716198	PW05
695172	7716052	PW06
695007	7716258	PW07
695181	7716373	PW08
695086	7715463	PW09
694837	7715448	PW10
694869	7715708	PW11
694570	7715476	PW12
694456	7715858	PW14
694564	7716541	PW15
695378	7713853	PW16
694258	7714411	PW17
694178	7716157	PW18
Fairview Farms Former Irrigation Wells		
695323	7712276	FF-04
695624	7710913	FF-06
Offsite Water Supply Wells		
697419	7711716	Sundial Marine
697670	7713200	Gresham Sand and Gravel
695286	7712544	FF-T01 (piezometer)
City of Portland Water Supply Wells (BLA)		
695059	7704601	COP-12
695639	7703193	COP-13
695632	7704118	COP-17
695379	7705178	COP-18
695454	7701737	COP-19
Geoprobes		
697835	7712607	GP-01
697874	7713034	GP-02
697818	7714520	GP-04
697855	7714888	GP-05
697743	7715403	GP-06
697650	7715769	GP-07
697493	7716115	GP-08
697206	7716451	GP-09
696859	7716630	GP-10
696321	7716871	GP-11
695973	7717115	GP-12
695736	7717353	GP-13
695422	7717879	GP-14
695252	7718259	GP-15
695163	7718403	GP-16
694962	7718009	GP-17
696009	7715954	GP-18
697488	7714942	GP-19
697015	7713496	GP-20
696546	7713407	GP-21
695365	7713957	GP-22

Appendix C
Groundwater Measurement Stations Represented With Fixed Nodes in the Site-Scale Groundwater Flow Model

Northing (NAD83/NAD91)	Easting (NAD83/NAD91)	Station Name
Geoprobes (continued)		
695445	7715443	GP-24
695461	7716860	GP-26
694403	7717269	GP-27
694320	7716477	GP-28
693805	7715908	GP-29
693799	7713561	GP-31
696259	7711129	GP-32
696282	7711946	GP-33
695764	7712989	GP-34
696839	7712138	GP-35
694904	7718818	GP-36
696528	7714876	GP-37
696441	7715210	GP-38
696425	7715501	GP-39
695944	7715532	GP-40
696051	7714853	GP-41
696153	7714421	GP-42
696296	7713369	GP-43
696960	7714198	GP-44
696269	7713883	GP-45
Bakehouse Sumps		
694877	7715538	SMP-1
694876	7715617	SMP-2
694875	7715694	SMP-3
694877	7715774	SMP-4
694868	7715855	SMP-5
694866	7715940	SMP-6
694859	7716089	SMP-7
694732	7715822	SMP-8
694729	7715918	SMP-9
694660	7716104	SMP-10
694596	7715618	SMP-11
694586	7715686	SMP-12
694588	7715808	SMP-13
694586	7715893	SMP-14
694483	7715437	SMP-15
694448	7715547	SMP-16
694469	7715639	SMP-17
694468	7715761	SMP-18
694444	7715844	SMP-19
694446	7715948	SMP-20
694365	7716123	SMP-21

APPENDIX D

Construction Summary of Groundwater Monitoring Wells, Production Wells, and Other Wells

01-JUNE-1999 9293817d.DWG

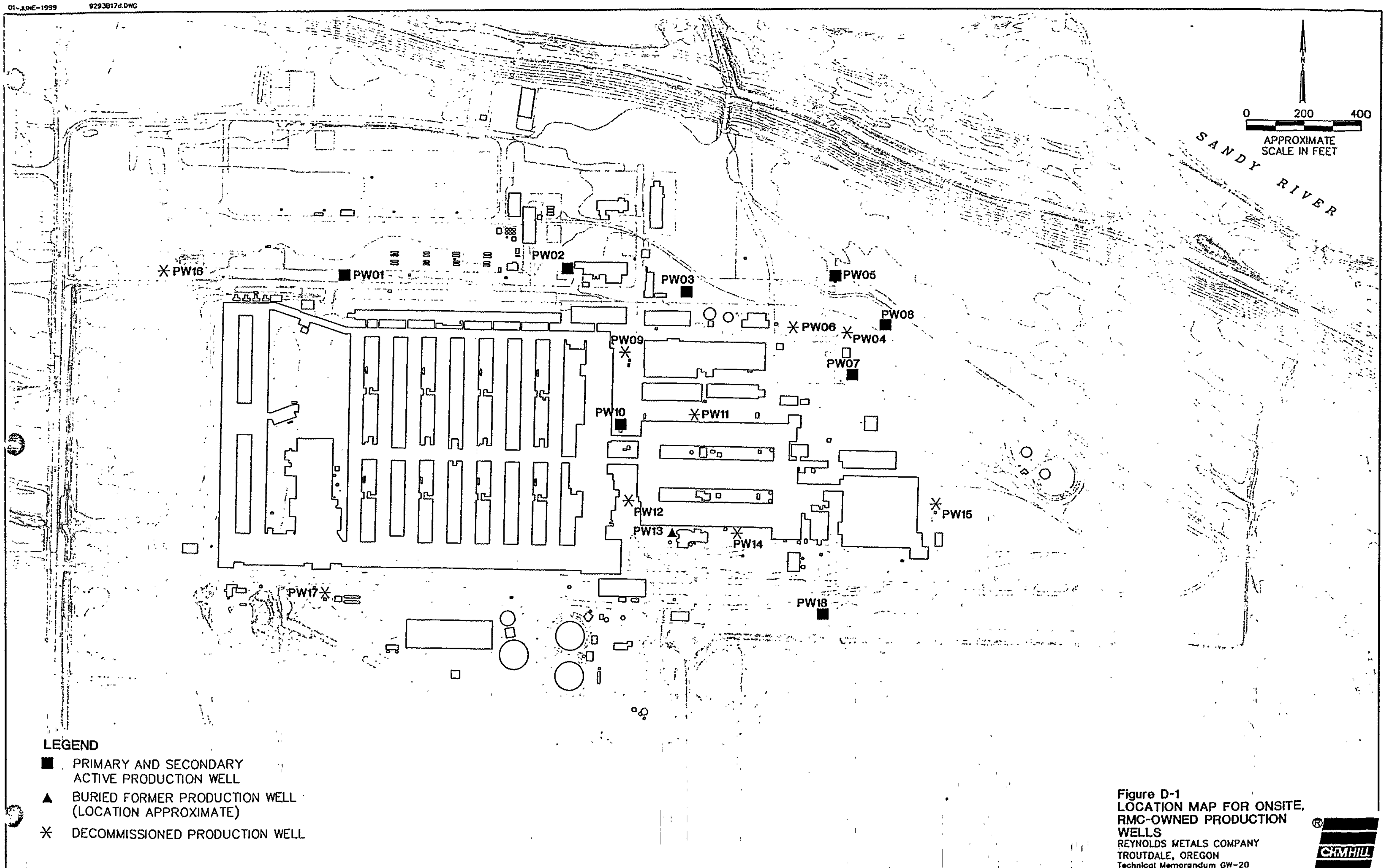


Figure D-1
LOCATION MAP FOR ONSITE, RMC-OWNED PRODUCTION WELLS
REYNOLDS METALS COMPANY
TROUTDALE, OREGON
Technical Memorandum GW-20

CH2MHILL

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Table D-1
Current Status and Construction of Production Wells

Well ID	Date Drilled	Well Status	Measuring Point Elevation (ft NGVD)	Measuring Access	Casing Diameter [inches, depth interval (ft)]	Total Depth (ft bgs)	Depth to Top of Screen (ft bgs)	Depth to Bottom of Screen (ft bgs)	Screened Geology	Video Survey Results
PW01	1942	Active/Backup	NA	No access	12"(0' - 282')	282	265	277	Loose gravel and conglomerate	NA
PW02	1942	Active/Backup	NA	No access	10"(0' - 268')	268	251	263	Very loose gravel and sandy gravel	NA
PW03	1942	Active	31.35	Probe only	12"(0' - 281')	281	253	264	Gravel and coarse gray sand	NA
PW04	1942	Decommissioned	24.46	Probe and transducer	12"(0' - 190')	190	170	180	Gravel and coarse sand	Total depth = 76 ft bgs
PW05	1943	Emergency fire pump	30.37	Probe/possible transducer	16"(0' - 277')	330	160 182 248	180 187 253	Cemented gravel and loose sand Loose sand/gravel with clay Tight gravel	NA
PW06	1948	Decommissioned	31.28	Probe and transducer	18"(0' - 193') 12"(180' - 279')	279	190 267	210 276	Coarse sand Loose sand with clay	12" casing 179 ft bgs Total depth = 190 ft bgs
PW07	1948	Active	31.35	Probe only	18"(0' - 203') 12"(190' - 254')	254	223 232	230 246	Blue/brown clay Loose gravel/sand	NA
PW08	1948	Inactive without pump	30.85	Probe only	18"(0' - 160') 12"(152' - 248')	248	158 195 210 235	174 206 218 242	Loose sand/gravel Loose sand/gravel Loose and cemented sand/gravel Sand and silt	NA
PW09	1949	Abandoned	28.21	Probe and transducer	20"(0' - 95.0') 12"(93' - 295') 8" (0' - 225') 6" (0' - 240')	295	120 185 217 245	165 191 240 255	Gray sand	Total depth by probing is approx. 99 ft bgs (Schneider, 7-28-95)
PW10	1949, 1955 [a]	Active	NA	No access	20"(0' - 140') 12"(0' - 625')	625	144 [b] 440 522 538	185 [b] 482 530 558	Sand and gravel Sand and gravel Sand and gravel	NA
PW11	1949, 1955 [a]	Decommissioned	30.7 Concrete 30.92 M.P.	Probe and transducer	20"(0' - 147') 12"(0' - 541')	592	147 [b] 417 502	187 [b] 434 533	Sand and gravel Sand and gravel	Perforations 411 to 432 ft bgs Perforations 497 to 499 ft bgs. Total depth = 499 ft bgs

Table D-1
Current Status and Construction of Production Wells

Well ID	Date Drilled	Well Status	Measuring Point Elevation (ft NGVD)	Measuring Access	Casing Diameter [inches, depth interval (ft)]	Total Depth (ft bgs)	Depth to Top of Screen (ft bgs)	Depth to Bottom of Screen (ft bgs)	Screened Geology	Video Survey Results
PW12	1949, 1954[c]	Decommissioned	29.19 TOC 30.76 concrete	Probe and transducer	20"(0' - 140') 16"(80' - 392') 12"(0' - 590')	584	147[d] 512 522 544 563	187[d] 518 538 555 578	Coarse sand Loose sand and gravel Loose sand and gravel Loose sand and gravel Loose sand and gravel	Perforations 510 to 516 ft bgs Perforations 520 to 535 ft bgs Perforations 544 to 556 ft bgs Perforations 563 to 569 ft bgs Total depth = 568 ft bgs
PW13	1949	Inaccessible	-	-	20"(0' -140') 12"(127' - 195')	195	143	190	Coarse sand, some small gravel	NA
PW14	1949, 1955[a]	Abandoned	28.37 TOC	Probe and transducer	26"(0' - 40') 20"(0' - 144') 12"(0' - 644')	644	150[b] 608	189[b] 637	Coarse sand, fine gravel Sand with gravel.	NA
PW15	1953	Decommissioned	NA	NA	NA	273	255	273	Sand and gravel	NA
PW16	1967	Decommissioned	24.46 access hole	Probe and transducer	16"(0' - 121') 12"(0' - 279')	279	151 256	192 269	Sand with some gravel Sand, silt, and gravel	Total depth = 276 ft bgs PVC pipe debris at well bottom
PW17	1969	Decommissioned	27.40	Probe and transducer	20"(0' - 63') 11"-12"(0' - 310')	310	170 221 280	207 238 300	Sand and fine gravel Sand, some gravel Sand, some gravel	Screened 163 to 201 ft bgs Screened 219 to 227 ft bgs Total depth = 275 ft bgs
PW18	1970	Active/Back-up	30.82	Probe only	11"-12"(0' - 270')	300	148 229	189 260	Sand and gravel	NA

Abbreviations:
bgs = below the ground surface
M.P. = measuring point
NA = not applicable
NGVD = National Geodetic Vertical Datum
PVC = polyvinyl chloride
TOC = top of casing

Note: Lithology and well construction from drilling logs and RMC files.

Footnotes:
[a] This well was deepened in 1955.
[b] This depth interval was perforated during the well's initial installation in 1949. This perforated interval was shut off when the well was deepened in 1955.
[c] This well was deepened in 1954.
[d] This depth interval was perforated during the well's initial installation in 1949. This perforated interval was shut off when the well was deepened in 1954.

Table D-2
Construction Summary of Groundwater Monitoring Wells and Other Wells
Reynolds Metals Company - Troutdale, Oregon

Well ID	Unit *(a)*	Installation Date	Total Depth *(b)*	Casing Diameter *(c)*	Borehole Diameter	Screen Length (feet)	Screened Interval *(b)*	Top of Filter Pack *(b)*	MPE *(d)*	GSE *(e)*	Screened Material *(f)*	Well Location *(g)*	Comments *(h)*
MW01-019	*S*	7/12/94	20	4-inch	12-inch	10	9 to 19	7	28.25	25.2	Sand (SP), Silt (ML)	Along South Ditch	
MW02-012	*S*	7/25/95	12.5	2-inch	10-inch	5	7 to 12	6	31.10	28.3	Silt (ML)	Scrap yard	
MW02-034	*UGS*	1/18/96	34	2-inch	10-inch	5	28 to 33	27	30.64	28.6	Sand (SP, SM)	Scrap yard	
MW03-017	*S*	7/9/94	18	2-inch	10-inch	8	9 to 17	7	29.69	27.4	Sand (SP, SM)	Perimeter	
MW03-098	*I*	6/26/96	100	2-inch	6-inch	10	88 to 98	87	30.65	28.7 *(j)*	Sand (SP)	Perimeter	
MW03-175	*D*	6/17/96	175.5	2-inch	6-inch	10	165 to 175	163.5	30.72	28.7 *(j)*	Sand (SP)	Perimeter	Borehole backfilled from 200 ft bgs
MW04-019	*S*	7/12/94	20	2-inch	12-inch	10	9 to 19	7	26.91	24.3	Silt (ML), Clay (CL)	South wetlands	
MW05-025	*S*	7/8/94	25	2-inch	10-inch	10	15 to 25	12	33.99	31.6	Silt (ML), Sand (SM)	Background	
MW06-024	*S*	7/8/94	25	2-inch	10-inch	10	14 to 24	11.5	26.81	24.1	Silt (ML), Sand (SP, SM)	Perimeter	
MW06-094	*I*	9/20/96	96	2-inch	6-inch	10	84 to 94	83.5	27.85	25.5	Sand (SW)	South of dike	
MW06-176	*D*	5/3/96	178	2-inch	6-inch	10	166 to 176	165	27.74	25.4 *(j)*	Sand (SW-SP)	Perimeter	Borehole backfilled from 197 ft bgs
MW07-024	*S*	7/9/94	25	4-inch	12-inch	10	14 to 24	12	28.38	28.7	Sand (SM), Silt (ML)	South of dike	
MW08-027	*UGS*	7/7/94	28	2-inch	10-inch	10	17 to 27	14	25.32	22.8	Sand (SP)	Perimeter	
MW08-127	*I*	7/10/96	129	2-inch	6-inch	10	117 to 127	116.5	25.62	23.5 *(j)*	Sandy gravel (GW)	Perimeter	Borehole backfilled from 134 ft bgs
MW08-169	*D*	5/23/96	170.5	2-inch	6-inch	10	159 to 169	158	25.88	23.7 *(j)*	Sand (SW) / Gravel (GW)	Perimeter	Borehole backfilled from 200 ft bgs
MW09-030	*UGS*	8/4/94	32	2-inch	10-inch	10	20 to 30	18	29.27	27.0	Sand (SP)	North landfill	
MW10-023	*S*	8/5/94	25	4-inch	10-inch	15	8 to 23	7	30.28	27.9	Silt (ML)	South of dike	
MW10-090	*I*	9/12/96	91	2-inch	6-inch	10	80 to 90	79	31.03	28.4	Sand (SW)	South of dike	
MW10-165	*D*	7/31/96	166	2-inch	6-inch	10	155 to 165	154	31.24	28.6	Gravel (GW)	South of dike	Borehole backfilled from 199 ft bgs
MW11-017	*S*	8/5/94	19	2-inch	10-inch	10	7 to 17	6	31.61	29.5	Sand/Silt (SP/ML)	East potliner	
MW12-021	*S*	8/4/94	23	2-inch	10-inch	5	16 to 21	14	22.53	20.2	Sand (SP) Silt (ML)	Perimeter	Borehole backfilled from 25 ft bgs
MW12-092	*I*	9/24/96	92	2-inch	6-inch	10	80 to 90	79	22.57	20.6	Sand (SW)	Perimeter	
MW12-184	*D*	5/21/96	184.5	2-inch	10-inch to 8.5 feet; 6-inch to 200 feet	10	174 to 184	171	23.04	20.7 *(j)*	Sand (SW)	Perimeter	Borehole backfilled from 200 ft bgs
MW13-022	*S*	7/12/95	23	2-inch	10-inch	5	17 to 22	15.5	30.88	28.3	Sand/silt (SP, SM) Sand (SP)	Scrap yard	
MW14-015	*S*	7/11/95	16	2-inch	10-inch	10	5 to 15	4	30.88	28.3	Silt (ML) Sand/silt (SP, SM)	Scrap yard	
MW15-024	*S*	7/13/95	24	2-inch	10-inch	10	14 to 24	11.5	22.75	20.9	Silt (ML) Sand/silt (SP, SM)	Perimeter	Borehole backfilled from 25 ft bgs
MW15-086	*I*	9/23/96	87	2-inch	6-inch	10	76 to 86	75	23.88	21.5	Sand (SW)	Perimeter	Borehole backfilled from 92 ft bgs

Table D-2
Construction Summary of Groundwater Monitoring Wells and Other Wells
Reynolds Metals Company - Troutdale, Oregon

Well ID	Unit (a)	Installation Date	Total Depth (b)	Casing Diameter (c)	Borehole Diameter	Screen Length (feet)	Screened Interval (b)	Top of Filter Pack (b)	MPE (d)	GSE (e)	Screened Material (f)	Well Location (g)	Comments (h)
MW15-175	*D*	6/4/96	175.8	2-inch	6-inch	10	165 to 175	164	23.88	21.8 *(j)*	Sand (SW)	Perimeter	Borehole backfilled from 200 ft bgs
MW16-014	*S*	7/13/95	14	2-inch	10-inch	8	6 to 14	4	28.91	26.7	Sand (SP)	South landfill	
MW17-016 **	*S*	7/21/95	17	2-inch	10-inch	5	11 to 16	10	27.13	24.8	Silt with sand (ML)	South wetlands	
MW17-028	*S*	7/21/95	28.5	2-inch	10-inch	5	23 to 28	22	27.30	24.8	Sand (SW), Silt (ML)	South wetlands	
MW18-016	*S*	7/20/95	16.5	2-inch	10-inch	5	11 to 16	9.5	23.98	21.5	Sand (SP)	South wetlands	
MW18-031	*UGS*	7/20/95	32	2-inch	10-inch	5	27 to 32	25	23.95	21.5	Silt (ML) Sand/silt (SP, SM)	South wetlands	
MW19-013	*S*	7/21/95	13.5	2-inch	10-inch	5	8 to 13	6.5	27.10	24.8	Sand (SW), Silt (ML)	South landfill	
MW20-026	*UGS*	9/1/95	26.5	2-inch	10-inch	10	16 to 26	15	28.46	25.8	Sand (SP)	North landfill	
MW21-012 **	*S*	9/5/95	12	2-inch	10-inch	5	7 to 12	6	24.54	22.4	Silt (ML)	North landfill	
MW21-025	*UGS*	9/5/95	25	2-inch	10-inch	5	19 to 24	17	24.60	22.0	Sand (SP)	North landfill	
MW21-063	*I*	10/1/96	65	2-inch	6-inch	10	53 to 63	51	26.76	23.8	Sand (SW)	North landfill	
MW21-176	*D*	8/14/96	177	2-inch	6-inch	10	166 to 176	165	26.01	23.3	Sand (SW)	North landfill	Borehole backfilled from 364 ft bgs
MW22-027	*UGS*	9/6/95	27	2-inch	10-inch	10	17 to 27	15	25.35	22.6	Sand (SP)	North landfill	
MW23-025	*UGS*	9/1/95	25	2-inch	10-inch	10	15 to 25	14	26.43	24.9	Sand (SP)	North landfill	
MW24-010	*S*	7/12/95	11	2-inch	10-inch	5	5 to 10	4	30.13	27.3	Sand/silt (SP, SM) Sand (SP)	Scrap yard	Borehole backfilled from 12.5 ft bgs
MW25-024	*S*	7/12/95	24	2-inch	10-inch	10	13 to 23	11.5	31.14	28.5	Silt (ML) Silty sand (SM)	Scrap yard	Borehole backfilled from 30 ft bgs
MW25-035	*UGS*	7/24/95	35.5	2-inch	10-inch	5	30 to 35	29	30.89	28.4	Sand (SW, SP)	Scrap yard	
MW26-012	*S*	7/24/95	12.5	2-inch	10-inch	5	7 to 12	6	26.26	23.9	Sand (SP)	South landfill	
MW27-045	*UGS*	11/1/96	45	2-inch	10-inch	10	35 to 45	32	31.66	29.6	Sand (SW)	Adjacent to Company Lake	
MW27-081	*I*	8/28/96	80.5	2-inch	6-inch	10	69 to 79	67.5	31.93	29.4	Sand (SW)	Adjacent to Company Lake	Borehole backfilled from 175 ft bgs
MW27-176	*D*	8/26/96	176.5	2-inch	6-inch	10	164 to 174	163	31.94	29.5	Gravel (GW)	Adjacent to Company Lake	Borehole backfilled from 260 ft bgs
MW28-160	*D*	10/10/96	161	2-inch	10-inch to 27 feet, 6-inch to 161 feet	10	150 to 160	148.7	28.62	28.8	Sand (SW)	Bakehouse	
MW29-033	*UGS*	10/31/96	33.5	2-inch	10-inch	10	23 to 33	21	29.75	27.9	Sand (SW)	South of dike	Borehole backfilled from 38.5 ft bgs
MW29-090	*I*	9/18/96	91	2-inch	6-inch	10	80 to 90	78	30.65	28.1	Sand (SW)	South of dike	
MW29-179	*D*	5/9/96	182	2-inch	10-inch to 18 feet, 6-inch to 182 feet	10	168 to 178	168	30.66	28.5 *(j)*	Gravel (GW-GM)	South of dike	Borehole backfilled from 200 ft bgs

Table D-2
Construction Summary of Groundwater Monitoring Wells and Other Wells
Reynolds Metals Company - Troutdale, Oregon

Well ID	Unit (a)	Installation Date	Total Depth (b)	Casing Diameter (c)	Borehole Diameter	Screen Length (feet)	Screened Interval (b)	Top of Filter Pack (b)	MPE (d)	GSE (e)	Screened Material (f)	Well Location (g)	Comments (h)
MW30-030	UGS	12/5/96	30	2-inch	10-inch	10	20 to 30	18	34.07	31.9	Sand (SW)	Near Gresham Sand & Gravel	
MW30-100	I	12/17/96	101	2-inch	6-inch	10	90 to 100	87	34.06	31.9	Sand (SW)	Near Gresham Sand & Gravel	
MW31-034	UGS	11/26/96	34	2-inch	10-inch	10	24 to 34	22	25.60	23.8	Sand (SW)	Fairview Farms	
MW31-095	I	12/9/96	96	2-inch	6-inch	10	85 to 95	82	25.00	22.8	Sand (SW)	Fairview Farms	Borehole backfilled from 120 ft bgs
MW32-040	UGS	12/6/96	41	2-inch	10-inch	10	30 to 40	28	28.44	28.4	Sand (SW)	Bakehouse	
MW32-095	I	12/6/96	95	2-inch	6-inch	10	85 to 95	82	28.31	28.4	Sand (SW)	Bakehouse	
MW32-165	D	12/2/96	165	2-inch	6-inch	10	155 to 165	151	28.40	28.4	Sand (SW)	Bakehouse	
MW33-033	UGS	12/4/96	33.5	2-inch	10-inch	10	23 to 33	22	29.92	28.5	Sand (SW)	Scrap yard	
MW33-095	I	11/25/96	95.5	2-inch	6-inch	10	85 to 95	82	30.56	28.5	Sand (SW)	Scrap yard	
MW33-165	D	12/30/96	165.5	2-inch	6-inch	10	155 to 165	152	30.68	28.7	Sand (SW), Gravel (GW)	Scrap yard	
MW34-038	UGS	12/3/96	38	2-inch	10-inch	5	33 to 38	31	32.12	30.3	Sand with silt (SW-SM) Sand (SW)	East potliner	
MW35-038	UGS	12/3/96	38	2-inch	10-inch	5	33 to 38	31	31.56	29.3	Sand (SW)	East potliner	
MW36-006 **	S	10/22/96	6.5	2-inch	9-inch	3	3 to 6	2	21.68	21.2	Silt (ML)	South wetlands	Borehole backfilled from 8 ft bgs
MW37-012	S	10/23/96	12.5	2-inch	9-inch	5	7 to 12	5	21.48	17.8	Silt (ML)	South wetlands	Borehole backfilled from 16 ft bgs
MW37-030	UGS	12/9/96	30.5	2-inch	9-inch	5	25 to 30	23	21.32	17.8	Sand with silt (SW-SM)	South wetlands	
MW38-007	S	11/1/96	7	2-inch	10-inch	4	3 to 7	2	22.56	20.6	Sand (SW)	Along Salmon Creek	
MW38-035	UGS	12/2/96	36	2-inch	10-inch	5	30 to 35	28.5	23.07	20.7	Sand (SW)	Along Salmon Creek	
MW39-095	I	6/26/97	95	2-inch	6.5-inch	10	85 to 95	82	25.18	22.3	Sand (SW)	Fairview Farms	
MW40-018	S	6/11/97	18.3	2-inch	11-inch	5	13 to 18	10	28.42	28.8	Silt (ML)	Bakehouse	
MW40-030	UGS	6/11/97	32	2-inch	11-inch	5	25 to 30	23	28.29	28.7	Sand (SW)	Bakehouse	
MW41-020	S	6/13/97	20.3	2-inch	11-inch	5	15 to 20	12	28.63	29.1	Silt (ML)	Bakehouse	
MW41-033	UGS	6/12/97	35	2-inch	11-inch	5	28 to 33	26	28.71	29.1	Sand (SM)	Bakehouse	
MW42-013	S	6/11/97	13.3	2-inch	11-inch	5	8 to 13	6	30.08	29.1	Silt (ML)	Bakehouse	
MW42-027	UGS	6/11/97	27.5	2-inch	11-inch	5	22 to 27	20	30.17	29.3	Sand (SW)	Bakehouse	
MW43-015	S	6/13/97	15.3	2-inch	11-inch	5	10 to 15	8	30.91	29.7	Silt (ML)	Bakehouse	
MW43-027	UGS	6/13/97	29	2-inch	11-inch	5	22 to 27	20	30.72	29.7	Sand (SW)	Bakehouse	
MW44-011	S	6/12/97	12	2-inch	11-inch	5	6 to 11	4	31.11	29.2	Sand (SW-SM) / Silt (ML)	Bakehouse	
MW44-027	UGS	6/12/97	27.5	2-inch	11-inch	5	22 to 27	20	30.88	29.2	Sand (SW)	Bakehouse	
MW45-017	S	6/17/97	17.8	2-inch	11-inch	5	12 to 17	10	30.61	28.7	Silt (ML)	Bakehouse	
MW45-042	UGS	6/16/97	43	2-inch	11-inch	5	37 to 42	35	30.26	28.9	Sand (SW)	Bakehouse	
MW46-018	S	6/16/97	18.8	2-inch	11-inch	5	14 to 19	11.5	31.48	29.6	Sand (SW) / Silt (ML)	Bakehouse	
MW46-043	UGS	6/16/97	43.3	2-inch	11-inch	5	38 to 43	36	30.99	29.4	Sand (SW)	Bakehouse	

Table D-2
Construction Summary of Groundwater Monitoring Wells and Other Wells
Reynolds Metals Company - Troutdale, Oregon

Well ID	Unit (a)	Installation Date	Total Depth (b)	Casing Diameter (c)	Borehole Diameter	Screen Length (feet)	Screened Interval (b)	Top of Filter Pack (b)	MPE (d)	GSE (e)	Screened Material (f)	Well Location (g)	Comments (h)
MW47-094	*I*	7/1/97	95	2-inch	6.5-inch	10	84 to 94	82	29.71	27.0	Sand (SW)	South landfill	
MW48-055	*I*	9/2/97	56	2-inch	6-inch	10	45 to 55	42	28.19	28.4	Sand	No. Side Casthouse	
MW48-165	*D*	8/27/97	199	2-inch	6-inch	10	155 to 165	151	28.12	28.3	Sand	No. Side Casthouse	Backfilled to 165 ft
MW49-095	*I*	10/29/97	95	2-inch	6-inch	10	84 to 94	81	30.52	28.7	Sand	Scrap Yard	
MW49-145	*D*	10/24/97	173	2-inch	6-inch	10	135 to 145	131	30.85	28.9	Sand	Scrap Yard	Backfilled to 146 ft
MW50-094	*I*	10/31/97	95	2-inch	6-inch	10	84 to 94	81	27.06	24.9	Sand	So. Side Casthouse	
MW51-069	*I*	11/3/97	69	2-inch	6-inch	10	58 to 68	55	26.17	23.4	Sand	Adjacent to River	Near Gresham S & G
MW52-045	*UGS*	10/30/97	45	2-inch	6-inch	10	35 to 45	31	26.43	23.8	Sand	Adjacent to River	Near MW08
MW53-034	*UGS*	10/31/97	35	2-inch	6-inch	10	24 to 34	21	23.80	20.6	Sand	Adjacent to River	East of East Lake
PZ17-019	*S*	10/29/97	19.3	1/2-inch	2-inch	3	16 to 19	14	28.73	NM	Silt	Bakehouse	Piezometer
PZ17-039	*UGS*	10/29/97	40	1/2-inch	2-inch	3	36 to 39	34	28.69	NM	Sand	Bakehouse	Piezometer
PZ18-023	*S*	10/31/97	23.3	1/2-inch	2-inch	3	20 to 23	18	27.87	NM	Silt	Bakehouse	Piezometer
PZ18-040	*UGS*	10/30/97	42	1/2-inch	2-inch	3	37 to 40	35	27.81	NM	Sand	Bakehouse	Piezometer
PZ19-014	*S*	10/31/97	14.3	1/2-inch	2-inch	3	11 to 14	9	29.30	NM	Silt	Bakehouse	Piezometer
PZ19-040	*UGS*	10/31/97	40	1/2-inch	2-inch	3	37 to 40	35	29.43	NM	Sand	Bakehouse	Piezometer
PW03	SGA	6/42	281	12-inch	12-inch	11	Perforated: 253 to 264	Not Known	NA	28.5	Gravel; coarse gray sand		RMC production well
PWO7	SGA	1948	254	24-inch from 0 to 40 feet; 18-inch from 0 to 203 feet; 12-inch from 190 to 254 feet	12-inch to 24-inch	NA	*Perforated:* 223 to 230; 232 to 246	Not Known	NA	28.5	Clay; Loose sand & gravel		RMC production well
PW08	SGA	1948	248	18-inch to 160 feet; 12-inch (152 to 248 feet)	12-inch	NA	158 to 174; 195 to 206; 210 to 218	Not Known	30.50	28.5	Loose sand & gravel; Loose sand & gravel; Loose & cemented sand/gravel		RMC production well
PW10	SGA	1949	625	20-inch to 140 feet; 12-inch from 0 to 625 feet	12-inch	NA	144 to 185; 440 to 482; 522 to 530; 538 to 558	Not Known	31.18	28.5	Sandy clay & gravel; Sand & gravel; Sand & gravel		RMC production well
PW18	SGA	1970	300	11-inch to 270 feet	Not Known	NA	148 to 189; 229 to 260	Not Known	30.57	28.0	Sand Sand & gravel		RMC production well

Table D-2
Construction Summary of Groundwater Monitoring Wells and Other Wells
Reynolds Metals Company - Troutdale, Oregon

Well ID	Unit (a)	Installation Date	Total Depth (b)	Casing Diameter (c)	Borehole Diameter	Screen Length (feet)	Screened Interval (b)	Top of Filter Pack (b)	MPE (d)	GSE (e)	Screened Material (f)	Well Location (g)	Comments (h)
Fairview Farms Well No. 4	SGA	1943 Well use: Irrigation	281	24-inch from 0 to 55 feet; 12-inch from 55 to 230 feet; 8-inch from 209 to 281 feet	Not Known	13	237 to 250	Not Known	22.41	19.1	Sand & gravel	~ 1,300 feet west of Sundial Road	Former irrigation well
Sundial Marine	SGA	12/19/79	233	6-inch from 0 to 227 feet	Not Known	5	228 to 233	Not Known	NA	NA	Sand & gravel	Northwest of Sundial Road, adjacent to Columbia River	Domestic well
Gresham Sand & Gravel	D	11/10/67	127	6-inch from 0 to 120 feet	Not Known	10	120 to 130	Not Known	NA	NA	Sand & gravel	Northwest of Sundial Road, adjacent to Columbia River	Domestic well

Notes:

(a) S = Shallow well screened in silt.
UGS = Shallow well screened in the upper gray sand.
I = Intermediate-depth well screened in sand.
D = Deep well screened in sand/gravel.
SGA = Deep production well screened in regional Sand and Gravel Aquifer (SGA).

** Well abandoned in June 1998.

(b) Feet below ground surface (ft bgs).
(c) Casing and screen constructed with flush-threaded Schedule 40 or 80 polyvinyl chloride with 0.010-inch machine-slotted screen.
(d) MPE = Measuring point elevation, feet 1929 National Geodetic Vertical Datum (NGVD).
(e) GSE = Ground surface elevation, feet 1929 NGVD.
(f) For explanation of soil classification codes, refer to ASTM D 2488, Standard Practice for Description and Identification of Soils (American Society for Testing and Materials, August 1990).
(g) Refer to Figures 1-4 for well locations.
(h) Each well is a groundwater monitoring well unless otherwise indicated.
(j) Reference point is top of concrete pad (feet 1929 NGVD), not ground surface elevation.
NA = information not available.

APPENDIX E

Elevation Data for the Base of the Silt Unit and the Top of the Older Rocks Unit

Table E-1
Elevation Data for the Base of the Silt Unit

Station ID	Easting (NAD83/NAD91)	Northing (NAD83/NAD91)	Silt Unit Base Elevation (NGVD 1929)
MW08-169	7714040	697826.20	16.8
MW20-026	7715342	696735.80	15.8
MW22-027	7714986	696969.00	14.6
MW23-025	7715126	697093.80	15.6
MW27-176	7713829	697220.60	10.5
MW28-160	7715664	694470.60	-9.2
MW29-179	7714523	695923.50	6.7
MW30-030	7712917	697369.30	20.9
MW31-034	7712742	696294.90	-2.2
MW32-165	7715477	695198.10	-1.6
MW33-033	7716534	694950.80	7.5
MW34-038	7717722	694644.50	-2.7
MW35-038	7717572	694469.40	0.3
MW39-095	7711971	696093.90	-17.7
MW47-094	7715894	693795.00	-18
MW48-165	7715055	695182.40	4.3
MW49-145	7717232	694572.90	-1.1
MW50-094	7715123	694174.00	-20.1
PW01	7714480	695359.50	3.5
PW02	7715262	695378.40	-3.4
PW03	7715678	695295.90	6.1
PW04	7716242	695149.80	5
PW05	7716198	695349.70	-14.6
PW06	7716052	695171.80	-18.7
PW07	7716258	695006.90	-7.9
PW08	7716373	695180.50	-12.5
PW09	7715463	695086.10	-9
PW10	7715448	694836.70	12.2
PW11	7715708	694868.80	-1.3
PW12	7715476	694570.50	-11.2
PW14	7715858	694455.60	-12
PW17	7714411	694258.10	-4.3
PW18	7716157	694177.60	-12.4
Boring M1	7713814	695286.00	-3
Boring M2	7713942	695208.00	-6
Boring M3	7713814	694871.00	-8
Boring M4	7713918	694737.00	-5.3
Boring M5	7713794	694608.00	-6
Boring M6	7713910	694478.00	-6.2
Boring M7	7713796	694266.00	-6
Boring M8	7713944	694151.00	-11.6
Boring M9	7713805	694021.00	-13
Boring M10	7714066	693960.00	-14.3
Boring N1	7714005	694568.00	-5.4
Boring N2	7714010	694383.00	-7.6
Boring N3	7714037	694620.00	-1.5
Boring N4	7713961	694502.00	-6.3
Boring O3	7715271	693966.00	-8.5
Boring O4	7715509	694140.00	-7.5
Boring O5	7715252	694028.00	-10
Boring O6	7715339	693966.00	-7.5
Boring O7	7715247	693992.00	-9
Boring P1	7715589	694446.00	-3
Boring P2	7715655	694433.00	0
Boring P3	7715687	694461.00	-3.2
Boring P4	7715748	694445.00	-2.5
Boring Q1	7714991	694161.00	-8
Boring Q2	7715030	694082.00	-11.5
Boring Q3	7715070	694162.00	-8
Boring Q4	7714771	694068.00	-10

Table E-2
Locations, Total Depth, and Stratigraphic Data for Monitoring Wells and Other Stations

Station ID	Northing (NAD83/ NAD91)	Easting (NAD83/ NAD91)	Ground Surface Elevation (feet NGVD)	Depth to base of Silt Unit (feet)	Elevation of Base of Silt Layer (feet NGVD)	Depth of Top of Older Rocks Unit (feet)	Elevation of Top of Bedrock (NGVD, ft)	Total Depth (ft)
RMC Monitoring Wells and Piezometers								
MW01-019	694112.5	7715540.0	25.2	Too shallow				20
MW02-012	694228.2	7716783.4	28.3					12.5
MW02-034	694229.5	7716768.3	28.6	24	4.6			34
MW03-017	693395.5	7716566.0	27.4					18
MW03-098	693409.4	7716573.0	27.4					100
MW03-175	693395.2	7716574.5	27.4	39	-11.6			175.5
MW04-019	694091.4	7714221.0	24.3	Too shallow				20
MW05-025	693928.0	7718662.0	31.6	Too shallow				25
MW06-024	696071.6	7713545.0	24.1					25
MW06-094	696094.6	7713543.6	25.5	20	5.5			96
MW06-176	696082.2	7713544.8	25.5					178
MW07-024	695727.2	7715718.0	28.7	Too shallow				25
MW08-027	697837.6	7714052.0	22.8					28
MW08-127	697826.2	7714040.2	22.8					129
MW08-169	697826.2	7714040.2	22.8	6	16.8	172	-149.2	170.5
MW09-030	697248.2	7715424.0	27.0					32
MW10-023	695179.7	7716965.0	27.9					25
MW10-090	695173.8	7716980.1	28.4					91
MW10-165	695176.6	7716973.6	28.6	30	-1.4			166
MW11-017	694394.3	7717692.0	29.5	Too shallow				19
MW12-021	694284.8	7713618.0	20.2					23
MW12-092	694282.1	7713629.3	20.6					92
MW12-184	694269.1	7713617.6	23.0	39	-16.0			184.5
MW13-022	694411.0	7716755.2	28.3	19	9.3			23
MW14-015	694403.1	7717247.1	28.3	Too shallow				16
MW15-024	695048.5	7713591.7	20.9					24
MW15-086	695066.6	7713593.2	21.5					87
MW15-175	695058.3	7713588.5	23.9	27	-3.1			175.8
MW16-014	693940.4	7716278.6	26.7	Too shallow				14
MW17-016	693358.2	7715618.9	24.8					17
MW17-028	693355.3	7715611.4	24.8	Too shallow				28.5
MW18-016	693636.3	7714147.3	21.5					16.5
MW18-031	693636.8	7714155.4	21.5	Too shallow				32
MW19-013	693896.8	7715939.2	24.8	Too shallow				13.5
MW20-026	696735.8	7715341.9	25.8	10	15.8			26.5
MW21-012	697186.8	7715625.6	22.4					12
MW21-025	697186.9	7715619.1	22.0					25
MW21-063	697205.0	7715609.4	23.8					65
MW21-176	697206.7	7715620.8	23.3	6	17.3	345	-321.7	177
MW22-027	696969.0	7714985.7	22.6	8	14.6			27
MW23-025	697093.8	7715126.0	24.1	10	14.1			25
MW24-010	694320.4	7716493.2	27.3	Too shallow				11
MW25-024	694137.4	7716760.2	28.5					24
MW25-035	694139.1	7716745.8	28.4	29	-0.6			35.5
MW26-012	693683.0	7715906.6	23.9	Too shallow				12.5
MW27-045	697218.7	7713869.8	29.6					45
MW27-081	697222.4	7713814.1	29.4					80.5
MW27-176	697220.6	7713828.3	29.5	19	10.5	221	-191.5	176.5
MW28-160	694470.6	7715663.5	28.8	58	-29.2			161
MW29-033	695924.9	7714493.3	27.9					33.5
MW29-090	695924.8	7714508.9	28.1					91
MW29-179	695923.5	7714523.1	30.7	24	6.7			182
MW30-030	697369.3	7712916.9	31.9	11	20.9			30
MW30-100	697376.5	7712923.2	31.9					101
MW31-034	696294.9	7712742.0	23.8	26	-2.2			34

Table E-2
Locations, Total Depth, and Stratigraphic Data for Monitoring Wells and Other Stations

Station ID	Northing (NAD83/ NAD91)	Easting (NAD83/ NAD91)	Ground Surface Elevation (feet NGVD)	Depth to base of Silt Unit (feet)	Elevation of Base of Silt Layer (feet NGVD)	Depth of Top of Older Rocks Unit (feet)	Elevation of Top of Bedrock (NGVD, ft)	Total Depth (ft)
MW31-095	696263.2	7712738.5	22.8					96
MW32-040	695184.6	7715476.7	28.4					41
MW32-095	695189.6	7715476.9	28.4					95
MW32-165	695198.1	7715477.2	28.4	30	-1.6			165
MW33-033	694950.8	7716533.8	28.5	21	7.5			33.5
MW33-095	694943.6	7716524.8	28.5					95.5
MW33-165	694936.5	7716519.7	28.7					165.5
MW34-038	694644.5	7717721.7	30.3	33	-2.7			38
MW35-038	694469.4	7717571.4	29.3	29	0.3			38
MW36-006	693711.1	7714956.9	21.2	Too shallow				6.5
RMC Monitoring Wells and Piezometers (continued)								
MW37-012	693631.5	7714741.1	17.8					12.5
MW37-030	693626.5	7714738.1	17.8	30	-12.2			30.5
MW38-007	693433.1	7714082.6	20.6					7
MW38-035	693443.4	7714083.4	20.7	30	-9.3			36
MW39-095	696093.9	7711970.4	22.3	30	-7.7			95
MW40-018	694884.1	7715596.3	28.8					18.3
MW40-030	694884.0	7715592.3	28.7	20	8.7			32
MW41-020	694993.7	7715460.1	29.1					20.3
MW41-033	694999.6	7715460.4	29.1	24	5.1			35
MW42-013	694865.0	7715956.8	29.1					13.3
MW42-027	694863.2	7715961.2	29.3	18	11.3			27.5
MW43-015	694979.8	7715870.6	29.7					15.3
MW43-027	694979.2	7715876.1	29.7	18	11.7			29
MW44-011	694671.8	7716135.7	29.2					12
MW44-027	694675.0	7716131.1	29.2	14	15.2			27.5
MW45-017	694416.8	7715845.6	28.7					17.8
MW45-042	694415.3	7715842.5	28.9	31	-2.1			43
MW46-018	694660.6	7715479.5	29.6					18.8
MW46-043	694660.5	7715475.0	29.4	34	-4.6			43.3
MW47-094	693795.0	7715893.9	27.0	45	-18.0			95
MW48-055	695182.7	7715046.2	28.4					56
MW48-165	695182.4	7715054.8	28.3	40	-11.7			199
MW49-095	694583.8	7717214.4	28.7					95
MW49-145	694572.9	7717231.5	28.9	35	-6.1			173
MW50-094	694174.0	7715123.0	24.9	45	-20.1			95
MW51-069	697752.3	7712711.3	23.4					69
MW52-045	697938.1	7713913.0	23.8					45
MW53-034	696211.9	7716996.9	20.6					35
RMC Production Wells								
PW01	695359.5	7714480.0	28.5	25	3.5			282
PW02	695378.4	7715262.0	28.6	32	-3.4			268
PW03	695295.9	7715678.0	31.1	25	6.1			281
PW04	695149.8	7716241.6	30.0	25	5.0			190
PW05	695349.7	7716198.0	30.4	45	-14.6			277
PW06	695171.8	7716052.0	31.3	50	-18.7			279
PW07	695006.9	7716258.0	31.1	39	-7.9			254
PW08	695180.5	7716373.0	30.5	43	-12.5			248
PW09	695086.1	7715462.6	30.0	39	-9.0			295
PW10	694836.7	7715448.0	31.2	42	-10.8	587	-555.8	625
PW11	694868.8	7715708.0	30.7	68	-37.3	561	-530.3	188
PW12	694570.5	7715476.2	30.8	42	-11.2			192
PW14	694455.6	7715858.2	30.0	42	-12.0			644
PW15	694563.9	7716541.4	27.8	bad data				275
PW16	695378.0	7713853.0	25.2	52	-26.8			303

Table E-2 Locations, Total Depth, and Stratigraphic Data for Monitoring Wells and Other Stations								
Station ID	**Northing (NAD83/ NAD91)**	**Easting (NAD83/ NAD91)**	**Ground Surface Elevation (feet NGVD)**	**Depth to base of Silt Unit (feet)**	**Elevation of Base of Silt Layer (feet NGVD)**	**Depth of Top of Older Rocks Unit (feet)**	**Elevation of Top of Bedrock (NGVD, ft)**	**Total Depth (ft)**
PW17	694258.1	7714411.0	27.7	3	24.7			310
PW18	694177.6	7716157.0	30.6	43	-12.4			300
PZ17-019 (piezometer)	694672.5	7715438.1	0.0					19.3
PZ17-039 (piezometer)	694671.0	7715433.1	0.0					40
PZ18-023 (piezometer)	694346.4	7715847.3	0.0					23.3
PZ18-040 (piezometer)	694346.8	7715842.5	0.0					42
PZ19-014 (piezometer)	694685.5	7716213.6	0.0					14.3
PZ19-040 (piezometer)	694684.9	7716218.5	0.0					40
Fairview Farms Former Irrigation Wells								
FF-04	695323.3	7712276.0	21.4					281
FF-06	695623.7	7710912.8	22.9					200
FF-T01 (piezometer)	695285.8	7712544.4	22.5					
Offsite Water Supply Wells Near Company Lake								
Sundial Marine	697419	7711716		0				233
Gresham Sand and Gravel	697670	7713200		0				130
Portland Water Bureau Monitoring Wells								
PWB-5D	694389.7	7708636.3	23.58	99	-75.42			261.5
PWB-5I	694381.6	7708645	23.47	99	-75.53			125
PWB-4D			29.29	6	23.29			217
PWB-4I			29.24	6	23.24			135
PWB-4S			29.19	6	23.19			62
BLA-2	694454.7	7706292.6	23.36	23	0.36			65
BLA-3	695035.4	7706252	21.53	41	-19.47			77
BLA-4			34.64	133	-98.36			163.5
Portland Water Bureau BLA Water Supply Wells								
COP-12			22.83	18				123
COP-13			27.39	25				171
COP-17			No data	25				194
COP-18			29.08	4				195
COP-19			24.81	25				123
Geoprobes								
GP-01	697835.1	7712606.6	12.9					
GP-02	697874.4	7713033.8	24					
GP-03	697935.8	7713921.5	23.1					
GP-04	697818.3	7714519.7	25.9					
GP-05	697855.3	7714887.8	13					
GP-06	697742.5	7715402.9	17.3					
GP-07	697649.8	7715768.5	23.3					
GP-08	697492.6	7716114.5	26.2					
GP-09	697205.8	7716450.7	26.3					
GP-10	696859.3	7716630.4	21.6					
GP-11	696321.2	7716871.1	28.1					
GP-12	695972.8	7717114.9	22.8					
GP-13	695736.4	7717353.4	22.5					
GP-14	695421.5	7717879.4	21.1					
GP-15	695251.9	7718258.6	22.3					
GP-16	695162.6	7718403.2	27.5					
GP-17	694962.2	7718009.1	28.7					
GP-18	696009.2	7715953.7	22.7					
GP-19	697488.4	7714941.6	30.2					
GP-20	697014.7	7713496.1	39					
GP-21	696546	7713407	40.1					
GP-22	695365.2	7713957.2	24.2					
GP-23	695179.3	7715054.6	28.3					

Table E-2 Locations, Total Depth, and Stratigraphic Data for Monitoring Wells and Other Stations								
Station ID	Northing (NAD83/ NAD91)	Easting (NAD83/ NAD91)	Ground Surface Elevation (feet NGVD)	Depth to base of Silt Unit (feet)	Elevation of Base of Silt Layer (feet NGVD)	Depth of Top of Older Rocks Unit (feet)	Elevation of Top of Bedrock (NGVD, ft)	Total Depth (ft)
GP-24	695445	7715442.6	28					
GP-25	695723.5	7715739.9	28.6					
GP-26	695461.2	7716860	29.2					
GP-27	694403.1	7717268.5	28.2					
GP-28	694320.4	7716476.5	27.3					
GP-29	693805	7715908.2	26.4					
GP-30	694168.8	7715123.9	24.5					
GP-31	693799.3	7713561	20.4					
GP-32	696259.3	7711128.5	21.6					
GP-33	696281.7	7711945.5	21					
GP-34	695764.3	7712988.9	22.8					
GP-35	696839.1	7712138.2	21.6					
GP-36	694903.9	7718818.4	23.6					
GP-37	696527.7	7714875.8	28.1					
GP-38	696441.2	7715210	27.9					
GP-39	696425.4	7715501.1	27.3					
GP-40	695944.4	7715532.3	27					
GP-41	696051	7714852.9	25.7					
GP-42	696152.5	7714421.3	25.3					
GP-43	696295.7	7713369.1	28.6					
GP-44	696960.3	7714197.5	20.7					
GP-45	696269.2	7713882.7	25.1					
Bakehouse Sumps								
SMP-1	694876.7	7715538.1	31.41					
SMP-2	694876.1	7715617	32.32					
SMP-3	694875.1	7715694.2	32.03					
SMP-4	694877.3	7715774.2	31.73					
SMP-5	694868.3	7715855.2	32.19					
SMP-6	694866.4	7715940.3	31.89					
SMP-7	694858.8	7716089.4	31.18					
SMP-8	694732.2	7715821.9	31.1					
SMP-9	694728.5	7715917.7	31.94					
SMP-10	694660.4	7716103.5	31.73					
SMP-11	694595.5	7715617.8	31.36					
SMP-12	694586	7715685.7	30.02					
SMP-13	694587.5	7715808.2	?					
SMP-14	694586.3	7715892.6	30.53					
SMP-15	694483.3	7715437.2	31.79					
SMP-16	694448.3	7715547.3	31.89					
SMP-17	694468.8	7715638.5	31.23					
SMP-18	694468.4	7715761	32.07					
SMP-19	694443.7	7715843.7	31.7					
SMP-20	694445.5	7715947.7	31.63					
SMP-21	694364.9	7716122.8	31.9					
South Wetlands Staff Gauges								
SG-7216	693657.2	7714071	12.7					
SG-7215	693715.3	7714062	15.1					
SG-7301	694098.4	7715852	16.7					
SG-5458	694082.2	7716444	20.9					
SG-5475	693757.5	7715698	16.1					
SG-5783	693639.5	7714932	15.7					

Table E-2 Locations, Total Depth, and Stratigraphic Data for Monitoring Wells and Other Stations								
Station ID	Northing (NAD83/ NAD91)	Easting (NAD83/ NAD91)	Ground Surface Elevation (feet NGVD)	Depth to base of Silt Unit (feet)	Elevation of Base of Silt Layer (feet NGVD)	Depth of Top of Older Rocks Unit (feet)	Elevation of Top of Bedrock (NGVD, ft)	Total Depth (ft)
Dames & Moore Borings								
Plant Expansion Bldg								
Boring 1			23.2	5	18.2			52.5
Boring 2			24.3	26	-1.7			62
Boring 3			22.7	16	6.7			57
Boring 4			23.7	29	-5.3			57
Boring 5			20	26	-6			56.5
Boring 6			21.8	28	-6.2			51.5
Boring 7			20.5	7.5	13			67
Boring 8			19.4	31	-11.6			72
Boring 9			18.5	26	-7.5			75
Boring 10			17.7	32	-14.3			69.5
Cast House								
Boring 1			28.6	34	-5.4			71.5
Boring 2			28.4	36	-7.6			42.5
Boring 3			28.5	30	-1.5			41
Boring 4			22.7	29	-6.3			35.5
Cryolite Recovery Plant								
Boring 1	No data							
Boring 2	No data							
Boring 3			32	40.5	-8.5			47.5
Boring 4			25	32.5	-7.5			52
Boring 5			32	42	-10			43
Boring 6			32	39.5	-7.5			41.5
Boring 7			32	41	-9			42.5
ESP Foundation								
Boring 1			29	32				50
Boring 2			29	29				51.5
Boring 3			29.3	32.5				47
Boring 4			29.5	32				47
Potroom Scrubber Bldg.								
Boring 1			24	32				61
Boring 2			22	33.5				75.5
Boring 3			24.5	32.5				75
Boring 4			22	32				58

Note: Entries in the "Ground Surface Elevation" column are measuring point elevations for the bakehouse sump.